INNOVATION AND RESEARCH FOR WATER INFRASTRUCTURE IN THE 21ST CENTURY: U.S. EPA's RESEARCH PLANS FOR GRAVITY SEWERS

Daniel J. Murray, Jr., P.E.
U.S. Environmental Protection Agency
Office of Research and Development
National Risk Management Research Laboratory
26 W. Martin Luther King Drive (MS-689)
Cincinnati, Ohio 45268

ABSTRACT

The U.S. Environmental Protection Agency's (EPA) Office of Research and Development (ORD) has long recognized the need for research and development in the area of drinking water and wastewater infrastructure. Most recently in support of the Agency's Sustainable Water Infrastructure activities, ORD put forth a proposal for a new research and development program entitled, **Innovation and Research for Water Infrastructure in the 21st Century**. The purpose of this program is to generate the science and engineering to improve and evaluate promising innovative technologies and techniques to reduce the cost and improve the effectiveness of operation, maintenance, and replacement of aging and failing drinking water and wastewater treatment and conveyance systems. The outputs from this program will assist utilities to more effectively implement comprehensive asset management, provide reliable service to their customers, and meet their Clean Water Act goals.

KEYWORDS

Wastewater infrastructure, condition assessment, system rehabilitation, innovative technologies, research and development

INTRODUCTION

Beginning in 2007, the U.S. Environmental Protection Agency's (EPA) Office of Research and Development (ORD) will support a new research program to generate the science and engineering to improve and evaluate promising innovative technologies and techniques to reduce the cost and improve the effectiveness of operation, maintenance, and replacement of aging and failing drinking water and wastewater conveyance and treatment systems. This research program directly supports the Agency's Sustainable Water Infrastructure Initiative. This paper will outline the plans for addressing condition assessment and rehabilitation needs for gravity sewer pipes in the U.S.

In 2002, the EPA's Office of Water (OW) carried out a study to gain a better understanding of the challenges facing the Nation's drinking water and wastewater utilities. EPA published **The Clean Water and Drinking Water Infrastructure Gap Analysis (EPA-816-R-02-020**), also known as the *"Gap Analysis*" report. The report identified several issues that raised concern as to the ability of utilities to keep up with their infrastructure needs in the future:

- Our wastewater and drinking water systems are aging, with some system components exceeding 100 years in age.

- The U.S. population is increasing and shifting geographically. This requires investment for new infrastructure in growth areas and “strands” existing infrastructure in areas of decreasing population.

- Current treatment may not be sufficient to address emerging issues and potentially stronger regulatory requirements.

- Investment in research and development has declined.

This paper addresses two major research areas identified as critical by EPA; condition assessment and system rehabilitation.

Condition assessment encompasses the collection of data and information through direct inspection, observation and investigation and in-direct monitoring and reporting, and the analysis of the data and information to make a determination of the structural, operational and performance status of capital infrastructure assets. Research issues in this area relate to the collection of reliable data and information and the ability of utilities to make technically sound judgments as to the condition of their assets. Condition assessment also includes the practice of failure analysis which seeks to determine the causes of infrastructure failures in order to prevent future failures.

System rehabilitation is the application of infrastructure repair and replacement approaches and technologies in an effort to return functionality to a wastewater system or sub-system. The decision-making process for determining the proper balance of repair and replacement is a function of the condition assessment, the life-cycle cost of the various rehabilitation options, and the related risk reductions.

While not addressed in this paper, two additional research areas have been identified in the plan by EPA for investigation: advanced concepts and integrated water resources and infrastructure management.

Advanced concepts relate to the application or adoption of new and innovative infrastructure designs, management procedures and operational approaches. The infusion of these advanced concepts into an established wastewater collection system is especially challenging. These innovative concepts can “evolve” in existing systems through system retrofit opportunities, but their compatibility with the in-place infrastructure system is critical. As existing systems expand with new development, the opportunity for the application of advanced concepts grows. These new sub-systems become opportunities for demonstrating the effectiveness of new and innovative concepts.

The plan recognizes that cost efficiencies and improved system performance can be realized with the application of **integrated water resources and infrastructure management.** The concepts of integrated management go beyond comprehensive asset management and include maximizing benefits from low impact development, water reuse, source water protection and watershed management. For utilities with responsibilities for and jurisdiction over both drinking water and wastewater systems, the institutional challenges to integrated management may be reduced. These utilities may be potential test beds for these integrated water resources and infrastructure management approaches.

CONDITION ASSESSMENT OF GRAVITY SEWERS

Since the passage of the Water Pollution Control Act Amendments, better known as the Clean Water Act (CWA), in 1972, the major focus of sewer system condition assessment and rehabilitation has been the reduction of infiltration and inflow (I&I). Requirements for sewer system assessments were codified in the Rules and Regulations for Sewer Evaluation and Rehabilitation (40CFR35.927) and stated that U.S. EPA construction grants could not be approved unless there was documentation that sewer systems contributing to municipal wastewater treatment plants were not exhibiting "excessive infiltration and inflow." (EPA, 1991)

Therefore, sewer system condition assessment and rehabilitation have focused primarily on the reduction of I&I. This has almost exclusively targeted condition assessment towards the reduction of excessive hydraulic loading in collection systems and at treatment facilities. (EPA, 1991) Most sewer system evaluations were driven solely to determine if excess flows were more cost effective to treat or remove. While I&I still plague our current wastewater collection systems, and is linked to our current challenges relating to sanitary sewer overflows (SSOs) and wastewater blending, the growing adoption of comprehensive asset management by utilities is broadening the focus of sewer system condition assessment. In addition to condition assessment that seeks to identify excessive hydraulic loading due to I&I, comprehensive asset management examines the likelihood that wastewater infrastructure will deteriorate and fail, and the consequences in terms of costs and the effect on the system's ability to deliver services to utility customers and meet a wide range of performance measures, especially environmental performance. (GAO, 2004)

As the focus of condition assessment continues to broaden to include targets beyond the reduction of excessive hydraulic loading due to I&I, sewer system inspection technologies and investigation approaches must evolve. More innovative technologies will take advantage of observation and detection technologies, such as sonar, laser, ultrasonic, and infrared, not traditionally applied to sewer system investigation. In addition, the deployment of these non-traditional technologies will be supported by emerging digital, modular, and robotics technologies to greatly expand the "reach" of sewer system inspection techniques. This shift will result in the collection and development of system knowledge that will guide utilities towards much better decision-making.

Corrosion of wastewater collection infrastructure, especially concrete sewers, is a significant cause of deterioration and premature failure. When exposed to the internal atmosphere of gravity sewers which is characterized by high humidity and the presence of hydrogen sulfide, sulfuric acid corrosion negatively affects concrete surfaces, mortar, and metal reinforcement material. Given this universal challenge for wastewater utilities, this research program will look carefully into the microbial environment of gravity sewers, especially as it relates to the presence of sulfate-reducing bacteria. This work will hopefully lead to innovative inspection technologies and condition assessment methods that address corrosion-related wastewater infrastructure issues.

Related to wastewater collection system inspection and condition assessment is the evaluation of sewer system security vulnerabilities. In today's climate, vulnerability assessment of the collection system should be an integral part of an overall system condition assessment program. A recent GAO report found that few utilities have or are planning to install monitoring or security devices to detect and prevent system intrusions. (GAO, 2006) Recent work, funded by EPA, has been conducted by the American Society of Civil Engineers (ASCE) and the Water Environment Federation (WEF) on monitoring systems and physical security enhancements, including security measures for wastewater collection systems.

State of the Technology

The ability to visually examine the internal condition of a gravity sewer using closed circuit television (CCTV) has been the most important development in the area of inspection and condition assessment, leading to the current operation, maintenance and rehabilitation techniques employed by wastewater utilities. Incremental improvements continue to be made to CCTV technology, and as electronic components become more affordable, this technology can be applied by most contractors and plumbers. Basic CCTV systems which can inspect small-diameter sewer and drain pipes can be purchased for less than $1500. Also, a standard investigation of a sewer line can cost a utility no more than $1 per foot. (WERF, 2004)

Most utilities have established fairly simple rating systems which use the results from CCTV investigations to make an overall assessment of each section of sewer being inspected. This rating can then be combined with other data and information, such as results from hydraulic evaluations, sewer location, known soil conditions, and operational records, to determine maintenance and system rehabilitation priorities. However, CCTV assessments are qualitative and rely heavily on the skill of the investigation personnel to make judgments on the condition of the sewer. Also, this technology does not provide quantitative data to determine variations in sewer dimensions, subtle deformations, or debris level. Also, CCTV does not permit assessment of pipe condition below the water line within a sewer. While many sewers can be inspected during dry weather conditions to minimize this limitation, most trunk sewers maintain a fairly high flow and diverting these flows for inspection purposes is difficult. (WERF, 2004)

The application of CCTV in combination with newer technologies is now emerging for use in sewer inspections. Sonar technology, which uses high-frequency sound waves, can identify defects, especially large cracks, in the wall of sewer pipes and because it is almost exclusively designed to work underwater, it can overcome one of the major shortcomings of CCTV. Laser technology can be used to identify variations in sewer pipes above the water line. Comparison of laser images of the interior dimensions of a sewer over time can be an effective method to determine temporal deterioration. (WERF, 2004)

One potential research issue emerges from this analysis of the state of technology for condition assessment. Given the ubiquitous application of CCTV for sewer inspections and condition assessment, a state of the art evaluation and technology transfer product on optimized application of CCTV results for condition assessment should be generated. Wastewater utilities that are well known for their innovative application of CCTV should be identified and a best practices assessment and tool produced. In addition, this effort could include optimizing the use of existing and historical data and information, in combination with CCTV information to establish baseline assessments.

Research Questions

The following key research questions relating to gravity sewer inspection and condition assessment have emerged from the research planning conducted by EPA. These key research questions reflect critical gaps in our knowledge of the performance of innovative inspection technologies, our understanding of proven condition assessment techniques, and our ability to diagnose and predict infrastructure failures.

- Can emerging and innovative inspection technologies, for both sewer and non-sewer assets, be identified and demonstrated in field settings to improve our understanding of their cost-effectiveness, technical performance, and reliability?

- Can advances in remote monitoring and wireless technologies be applied to develop in-system and in-pipe sensor systems, including real-time data collection, reporting and assessment, to reduce confined-space entry requirements for sewer system inspection and investigation?

- Can correlations be established between the assessed condition and measures of the performance, operation, or internal environment of sewers and non-sewer assets which could lead to the use of innovative indicators to determine and track the condition of assets over time?

- Can standard technical guidelines, uniform data requirements and indicators be developed for condition assessment of sewers and non-sewer assets, including manholes, service laterals and pipe joints?

- Can technical guidance be developed for establishing an overall wastewater infrastructure inspection program, including inspection prioritization, inspection frequency, inspection type (physical vs. visual, maintenance vs. structural), inspection by asset type, and inspection cost-effectiveness?

- Can cost-effective and reliable methods for the identification and assessment of wastewater exfiltration be developed?

- Can the dynamics of wastewater collection system infrastructure failure be better diagnosed and understood to model and forecast the remaining life of assets, prioritize the investigation of asset failures of high consequence, and conduct reliable infrastructure failure risk assessments in support of comprehensive asset management?

Proposed Research

Based upon the key research questions presented above and the known research projects that are ongoing or recently completed by other stakeholders, the following research, demonstrations and technology transfer products are currently being considered by EPA. Each proposal indicates the time frame for the work.

Technology Transfer Product: Optimization of Closed Circuit Television Inspection Data and Information for Effective Condition Assessment – A comprehensive evaluation of the state of the art of CCTV inspection of wastewater collection systems. (6-9 months)

Technology Demonstration Program: Emerging and Innovative Technologies for the Inspection of Wastewater Collection Systems – An inspection technology demonstration program, conducted in cooperation with wastewater utilities. (36-48 months)

Applied Research Review and Evaluation: Understanding the Forensics of Sewer Failures to Support Failure Forecasting Model Development – A comprehensive evaluation of our ability to conduct forensic studies of sewer failures, to understand the critical factors that cause sewer system failures, and our ability to model and forecast future failures to support comprehensive asset management. (12-18 months)

Technology Transfer and Development Program: **Cross-Sector Transfer and Application of Advanced and Remote Sensing Technologies for Wastewater Collection System Monitoring –** A comprehensive review of new, innovative pipeline monitoring technologies that apply advanced and remote sensing approaches. Many of these innovative pipeline monitoring technologies have been developed for application in sectors other than the drinking water and wastewater industries, such as the gas and petroleum pipeline industry. (24-36 months)

Innovative Condition Investigation Method Development: Advanced Techniques for Detecting Exfiltration and Crown Corrosion Conditions – The exploration of using advanced molecular/microbiological techniques for identifying the presence of sulfate-reducing bacteria *(Desulfovibrio desulfuricans)* to assess the probability of crown corrosion in sewers; and using isotope tracers to indicate exfiltration from sewer lines. (18-30 months)

Technology Application Methodology Development: Tools for Inspection Program Prioritization – A tool or tools for assisting wastewater utilities in prioritizing sewer inspections, selecting the appropriate technology and inspection technique, and establishing inspection frequency based on a risk-based methodology. (18-30 months)

SYSTEM REHABILITATION OF GRAVITY SEWERS

The objective of system rehabilitation is to ensure the overall viability of the collection system to maintain operational and structural integrity, and to prevent or reduce infiltration, inflow and exfiltration, and their negative environmental impacts. There are several primary concerns related to deteriorating sewers. Water that flows into sewer pipes through defects (holes, cracks, failed pipe joints) can weaken the critical soil-pipe structure. Fine soil particles carried into the sewer can eventually reduce soil support to a point causing pipe deformation and/or subsidence. Exfiltration of water from the sewer into the surrounding soil can also weaken support provided by the soil. Soil movement due to traffic movement can exceed design assumptions and result in soil-support related problems. Deposition of material and sewer blockages can result in septic conditions due to flat grades, high ambient temperatures and poor ventilation. These conditions are ideal for the development of sulfuric acid and resulting crown corrosion which reduces the structural integrity of the concrete and the reinforcing steel. High rates of infiltration and inflow can lead to sewer overflows, basement backups and excessive peak flows at the treatment plant. Exfiltration of sewage into the surrounding soil can lead to groundwater and soil contamination. In some instances, water pressure drops in water distribution pipes adjacent to exfiltrating sewers can result in contamination of the potable water supply. Lastly, inadequate inspection and quality assurance during sewer installation can result in long-term problems due to poor workmanship. (Tafuri and Selvakumar, 2002)

Generally, rehabilitation includes a broad spectrum of approaches, from repair to replacement that attempt to return the system to near-original condition and performance. Repair techniques are used when the existing sewer is structurally sound, provides acceptable flow capacity, and can serve as the support or host of the repair method. When the existing sewer is severely deteriorated, structurally unsound, or increased flow capacity is needed, it is usually replaced. A wide range of causes can be responsible for sewer line deterioration and failure. These include:

- inadequate or improper bedding material,
- chemical attack,
- traffic loadings,
- soil movements,
- groundwater fluctuations,
- poor design and installation, and
- inadequate maintenance. (WERF, 2000)

Effective system rehabilitation programs require a complete understanding of the condition and performance of the collection system, including factors that affect system integrity and operations. While pipe age is an important factor, it is usually a combination of several factors that causes failures and influences rehabilitation decisions, leading to a very complex decision-making process. Pipe materials, bedding and backfill materials, surrounding soil conditions, loads and stresses on the pipe, groundwater levels, sewage and soil acidity, sewage dissolved oxygen levels, and electrical and magnetic fields are factors that negatively impact long-term integrity and operational performance of the collection system. The results from a well designed collection system inspection and condition assessment program provide critical input to decision support tools that evaluate the condition of the system based on structural, hydraulic, service delivery, water quality and economic factors.

Building connections to street sewers, referred to as house or service laterals, can contribute as much as 70 to 80% of the infiltration to a sewer. Fluctuating ground water, variable soil characteristics and conditions, traffic, erosion, washouts, etc., cause enormous stresses on house/service lateral pipes and joints. Connectors and fittings in many cases do not retain their watertight integrity while adjusting to these factors. Some connections react to soil acid and may totally disintegrate in a few years. These conditions often result in generating major points of infiltration at the connection of the house/service lateral to the sewer main. With current technology, rehabilitating building connections may not be economically feasible because of the shear number of connections. The problem is both critical and sensitive because of private ownership and the costs associated with disturbance to the occupant and damage to private property. Because of this, municipalities are often reluctant to address infiltration and inflow problems from these sources. (Tafuri and Selvakumar, 2002)

State of the Technology

Collection system rehabilitation includes a wide range of repair and replacement options that can be used to return the system to acceptable levels of performance. Pipeline rehabilitation procedures are usually preceded by some form of cleaning to remove foreign materials before other phases of rehabilitation are implemented. The removal of roots, sediments, and debris is also a critically important practice for maintaining operational performance levels including ensuring proper flow conditions, reducing infiltration and exfiltration, and preventing structural damage to the pipeline. Common repair methods of chemical and cement grouting address problems associated with groundwater movement, washouts, soil settlements, collapses, and soil voids. Grouting is effective in reducing or eliminating infiltration, but will not significantly improve the sewer's structural condition. It does, however, help stabilize the surrounding soil mass. Other system repair approaches include sliplining, spiral-wound pipe, segmented liner pipes, cured-in-place pipe (CIPP), fold and form pipe, close-fit-pipe, coatings, mechanical sealing devices, and spot repair. Many rehabilitation methods reduce pipe cross-sectional area, possibly reducing hydraulic performance.

Trenchless technologies have moved to the forefront sewer system rehabilitation. Many are proprietary systems and the details of installation procedures and materials are trade secrets, limiting the ability to compare and evaluate competing approaches. For some of the technologies, techniques, codes, and standards have been developed; however, because of the rapidly evolving technology in rehabilitation, standards and codes often lag behind. Trenchless technologies are applied in both repair and replacement situations. Pipe replacement technologies include pipe bursting, pipe splitting, pipe reaming, and pipe eating. These trenchless replacement techniques install a new sewer in the location of the old pipe with limited surface disturbance and minimal disruptions to traffic and businesses.

It is significant to mention that past studies have found that rehabilitation of sewers at the street alone does not completely solve the infiltration problem. Successive rainfalls can elevate the groundwater table to levels where entry occurs through service laterals, as previously mentioned. When performed, rehabilitation of service laterals is done by point repair or replacement; sliplining and pipe bursting are sometimes used. These approaches do not overcome the private ownership problem or the problems associated with the location and configuration of the line (such as sharp bends in the line).

System rehabilitation includes repairing or replacing appurtenances (manholes, pump stations, wet wells, and siphons) which is an important component of a comprehensive program. About 30 to 50 percent of system infiltration and inflow is due to defects in or near appurtenances, in particular, manholes. For example, manhole covers submerged in one inch of water can allow as much as 75 gallons per minute to enter the system depending on the number and size of holes in the cover. Rehabilitation of manholes, pump stations, and wet wells includes spray-on coatings, spot repairs, structural liners, and replacement. Rehabilitation of siphons includes some of the options available for pipelines such as grouting and lining. Many siphons have been rehabilitated using either cured in place pipe (CIPP) or high density polyethylene (HDPE) liners. (Tafuri and Selvakumar, 2002)

Selection of rehabilitation methods and materials suitable for various parts of the wastewater collection system remains an issue, especially due to the seemingly endless emergence of new materials. Uncertainty in the selection of appropriate repair and replacement techniques is partly related to the lack of understanding of the capabilities of each methodology to solve the problem in the long term. Reliable rehabilitation product performance under actual field conditions, especially over longer periods of performance, is lacking. Data on the effectiveness and longevity of rehabilitation technologies and materials and life-cycle cost information will be useful in determining whether rehabilitation or replacement is more cost effective.

The introduction of sewer pipes made from new plastic materials is challenging the more traditional sewer pipes constructed from concrete, clay and ductile iron. Plastic has been, and continues to be, an innovative material for sewer pipes. The most commonly used materials for wastewater applications are polyvinyl chloride (PVC), polyethylene (PE) and glass reinforced plastic (GRP). Plastic pipe innovations include structured wall pipe and composite pipe that use different pipe materials to address both structural and corrosion issues. The application of plastic pipe in wastewater is fairly new resulting in the need for determining long-term performance and related testing. In addition, raw materials and formulations can vary widely, resulting in different quality pipe for the same plastic.

Research Questions

The following key research questions relating to gravity sewer system rehabilitation have emerged from the research planning by EPA. These key research questions reflect critical gaps in our knowledge of the performance of innovative rehabilitation technologies, our understanding of the long-term performance and cost of sewer pipe made from new materials, and our ability to determine the most long-term cost effective rehabilitation methods for the situation being addressed.

- Can emerging and innovative sewer system rehabilitation technologies, for both sewer and non-sewer assets, be identified and demonstrated in field settings to improve our understanding of their cost-effectiveness, technical performance and reliability?

- Can approaches and methods be developed for determining the long-term performance and life-cycle cost effectiveness of various system rehabilitation technologies, including new and existing materials?

- Can guidance be provided for establishing a comprehensive system rehabilitation program, including rehabilitation of non-sewer assets, selection of pipe and rehabilitation materials, and testing and quality assurance of field installation and application of rehabilitation technologies?

- Can guidance be provided for collection system operation and maintenance programs, including procedures to assess and optimize maintenance practices that reduce the need for rehabilitation?

- Can sewer and collection system design guidance based on lessons learned from system rehabilitation be developed to enhance long-term performance and system integrity?

- Can a sound, risk-based, decision-making process for selecting optimal system rehabilitation technologies and methods be developed based on long-term effectiveness, system performance, structural integrity, consequence of failure, and life-cycle cost?

Proposed Research

Based upon the key research questions presented above and the known research projects that are ongoing or recently completed by other stakeholders, the following research, demonstrations and technology transfer products are being considered. Each proposal indicates the time frame for the work.

Technology Transfer Products: Collection System Rehabilitation Methods and Technologies – State of the Technology. A series of products that present the current state of the art in the rehabilitation of sewer and non-sewer assets. The first phase of this project will be to conduct an international technology forum to develop a comprehensive inventory of rehabilitation technologies being applied around the world. The second phase of the project will be the development of a series of technology capsule reports that will transfer performance and cost information on rehabilitation technologies using case-studies. (9-36 months)

Technology Demonstration Program: Emerging and Innovative Technologies for Wastewater Collection System Rehabilitation – A rehabilitation technology demonstration program, conducted in cooperation with wastewater utilities (36-48 months)

Technology Transfer Product: **Inspection and Quality Assurance Procedures for Installation and Application of Collection System Rehabilitation Methods and Technologies.** This product will provide technical guidance on the development and implementation of testing and quality assurance practices for field installation of rehabilitation (repair and replacement) of sewer and non-sewer assets. This guide will examine best practices selected from wastewater utilities, vendors and industry. The goal of the product will be to reduce long-term rehabilitation requirements by improving installation practices and collecting critically needed "as built" information for future rehabilitation decision making. (12-24 months)

Technology Transfer Product: Collection System Sewer Pipe Selection Guide. This product will be a comprehensive guide for the selection of sewer pipe for use by wastewater utilities and consulting engineers. This guide will include both traditional and new pipe materials. The selection matrix will present advantages and disadvantages of various pipe materials and pipe designs for use in a wide variety of conditions and applications. (9-18 months)

Applied Research and Review: Collection System Design Based on Lessons Learned from System Rehabilitation. This research effort will look at experience from sewer repair and replacement to determine if approaches for sewer designs can be improved to enhance long-term performance and structural integrity. As collection systems undergo inspection, condition assessment and rehabilitation, data and information that could improve system designs are collected. This effort will review and evaluate those data and information to identify trends and implications on system design. The outcome will be technical guidance on using experiences from rehabilitation to improve site-specific designs as well as general design practices where possible. (12-36 months)

Updated Technology Transfer Product: Design Manual – Odor and Corrosion Control in Sanitary Sewerage Systems and Treatment Plants. This will be an update of the EPA design manual published in 1985 (EPA/625/1-85/018). This updated manual will reflect changes in technologies and practices for controlling odor and corrosion in existing and new collection and treatment systems developed over the last twenty years. Especially important will be the application of new materials that are designed to be corrosion resistant. (6-18 months)

CONCLUSIONS

Our nation is facing critical challenges as our wastewater infrastructure is aging. While we know that aging cannot be reversed, we must develop the knowledge of our wastewater collection and treatment systems to make reliable diagnoses and propose cost-effective interventions. Not unlike a doctor, utilities should strive to gather the most insightful information and use the latest treatment approaches to keep their systems healthy and to increase system life expectancy. This is, and will continue to be, no easy task. In addition, with the knowledge gained, utilities can begin to design new systems that are more sustainable and reflect the evolution of urban wastewater infrastructure that will result from the application of new and innovative technologies and management approaches. Our research program is designed to provide the tools needed to apply new and innovative technologies and to help utilities to become more cost-effective stewards of our nation's wastewater infrastructure.

REFERENCES

Tafuri, Anthony, N. and Ariamalar Selvakumar, Wastewater Collection System Infrastructure Research Needs in the USA, Urban Water, Vol. 4, Issue 1, 2002.

U.S. Environmental Protection Agency, Handbook – Sewer System Infrastructure Analysis and Rehabilitation, EPA/625/6-91/030, October 1991.

U.S. Government Accountability Office, Water Infrastructure – Comprehensive Asset Management Has Potential to Help Utilities Better Identify Needs and Plan Future Investments, GAO-04-461, March 2004.

Water Environment Research Foundation, An Examination of Innovative Methods Used in the Inspection of Wastewater Systems, 01-CTS-7, 2004.

Water Environment Research Foundation, New Pipes for Old: A Study of Recent Advances in Sewer Pipe Materials and Technology, 97-CTS-3, 2000.