EPA/600/X-09/003 | April 2007 | www.epa.gov/nrmrl

United States
Environmental Protection
Agency

Innovation and Research for Water Infrastructure for the 21st Century

RESEARCH PLAN

Office of Research and Development
National Risk Management Research Laboratory - Water Supply and Water Resources Division

EPA/600/X-09/003
April 2007

U.S. Environmental Protection Agency
Office of Research and Development

Innovation and Research for Water Infrastructure for the 21st Century Research Plan (4/30/07)

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Executive Summary

Beginning in Fiscal Year 2007, the U.S. Environmental Protection Agency's (EPA) Office of Research and Development (ORD) will be supporting 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 treatment and conveyance systems. This research program directly supports the Agency's Sustainable Water Infrastructure Initiative (www.epa.gov/waterinfrastructure).

The program has been identified in the President's Fiscal Year 2007 Budget to receive $7 million per year ($5 million wastewater, $2 million drinking water). The outputs from this program will assist EPA's program and regional offices, states and tribes to meet their programmatic requirements and utilities to more effectively implement comprehensive asset management, provide reliable service to their customers, and meet their Clean Water Act and Safe Drinking Water Act requirements. This research program recognizes that an essential component of planning for water infrastructure is incorporating security aspects. Thus, the program will coordinate with the water security program at the National Homeland Security Research Center.

This plan was developed in collaboration with key internal and external stakeholders. Key internal stakeholders include the Office of Water and the EPA's Regional Offices. Important external stakeholders include drinking water and wastewater utilities, the Water Environment Research Foundation, the American Water Works Association Research Foundation and many other federal, state and local agencies and departments, professional and trade associations, and academia. The plan recognizes that stakeholder involvement and collaboration are critical to the success of the planning, implementation and communication of this research program.

In March 2006, over 50 individuals representing key stakeholder organizations and considered technical experts in the field were brought together for a two-day workshop to identify research needs relating to drinking water and wastewater infrastructure. The products from that workshop were a detailed meeting report (EPA, 2006a) and a comprehensive research issues report (EPA, 2006b) that served as foundation documents and helped to identify critical research gaps that led to the recommendations in this plan.

The plan proposes work relating to condition assessment, system rehabilitation, advanced concepts and innovative treatment technologies. Each section of this plan presents important background information; analyzes the "state of the technology" and poses important research questions that need to be answered to move the "state of the technology" forward through innovation. The following high priority research, demonstration and technology transfer projects are some that are proposed to help address the research questions:

Condition Assessment of Wastewater Collection Systems:

- Technology Demonstration Program: Emerging and Innovative Technologies for the Inspection of Wastewater Collection Systems
- Technology Transfer Product: Optimization of Closed Circuit Television Inspection Data and Information for Effective Condition Assessment

Condition Assessment of Water Distribution Systems:

- Project Selection Tools: Value of Condition Assessment
- Basic and Applied Research: Investigations of Causes, Mechanisms and Predictability of Failure to Enhance Condition Assessment Capability

System Rehabilitation of Wastewater Collection Systems:

- Technology Transfer Products: Collection System Rehabilitation Methods and Technologies – State of the Technology
- Technology Demonstration Program: Emerging and Innovative Technologies for Wastewater Collection System Rehabilitation

System Rehabilitation of Water Distribution Systems:

- Applied Research: Rehabilitation vs. Replacement Decision-making
- Technology Demonstration/Verification Program: Emerging and Innovative Technologies for Pressure Pipe Rehabilitation

Advanced Concepts for Wastewater Collection-Treatment Systems:

- Develop and demonstrate innovative integrated sewerage system designs for new urban areas, retrofitting existing urban areas, retrofitting existing combined sewer systems (CSS), and upstream additions to existing CSS
- Conduct a worldwide search of the literature (including grey literature[1]), WERF, AWWARF, EU, and other international organizations covering advanced sewerage-system design and technology and from that effort, develop a refined research, development and demonstration strategy

[1] Grey literature – "Non -conventional literature (NCL, also called 'grey literature') comprises scientific and technical reports, patent documents, conference papers, internal reports, government documents, newsletters, factsheets and theses, which are not readily available through commercial channels. NCL specifically does not include normal scientific journals, books or popular publications that are available through traditional commercial publication channels." en.wikipedia.org/wiki/Grey_literature

Advanced Concepts for Drinking Water Distribution Systems:

- Retrospective and Prospective Assessments of Dual Systems for Potable and Non-potable Uses
- Evaluate and Improve Distribution System Models

Innovative Treatment Technologies for Wastewater and Water Reuse:

- Nitrogen Control and Phosphorus Removal Technology Design Manuals
- Water Reuse Applications of Wastewater Treatment Technologies
- Wastewater Treatment Technology Evaluations

In addition, the proposed research, demonstration and technology transfer projects presented will include work in several cross-cutting areas. Addressing these areas may require focused research efforts or may require issue integration into broader research projects. These cross-cutting areas include:

- Cost, cost effectiveness, cost benefit, and life-cycle costing
- Performance and outcome measurement
- Technology baseline development and "state of the technology" evaluations
- Decision support systems
- Systems modeling
- Integrated management systems

The plan recognizes that accountability is critical to the success of the program. Throughout the implementation of the plan, clear and concise project performance indicators and programmatic outcome measures will be developed and tracked. It is anticipated that these gauges of success will include a range of human health, environmental, cost-effectiveness, infrastructure performance, and customer service criteria. Also, the utility of program products will be evaluated through interaction with customers, including the Office of Water, EPA Regional Offices, state drinking water and water quality departments, and drinking water and wastewater utilities. It is anticipated that project performance indicators will be project-specific and developed as part of project planning. Programmatic outcome measures will be developed and identified during the early stages of program implementation. To the extent possible, these outcome measures will utilize data and information currently being collected that can provide baselines and comparative analysis for a comprehensive, national view of program effectiveness.

The plan also provides preliminary sequencing of projects and resource estimates for a 5-year time period. The implementation of this plan and final project timelines and resource requirements will be the product of a dynamic process that will permit modifications to the plan, as needed. As this plan is implemented and internal and external stakeholders are engaged and new knowledge of ongoing research is attained, this plan will be reshaped to keep it current.

This plan will become a tool for the Agency and ORD to demonstrate national leadership through collaboration with our many stakeholders. One means to show national leadership would be the establishment of a sustainable water infrastructure management and design research center. This center of excellence in research for drinking water distribution systems and wastewater collection systems infrastructure would be a competitively awarded, academic research center. It is anticipated that this center will be a collaboration between several universities that will come together to establish nationally recognized expertise to conduct cutting edge research. This research center would establish a robust research program in cooperation with ORD and key stakeholders. ORD has engaged the National Science Foundation (NSF) and has established shared goals of collaborative research efforts, including the potential for establishing an EPA-NSF engineering research center.

References

U.S. Environmental Protection Agency. 2006a. Innovation and Research for Water Infrastructure for the 21st Century – EPA Research Planning Workshop – Draft Meeting Report, March.

U.S. Environmental Protection Agency. 2006b. Innovation and Research for Water Infrastructure for the 21st Century – Water and Wastewater Infrastructure Draft Research Issues Report, June.

Introduction

Purpose

This plan has been developed to provide the Office of Research and Development (ORD) with a guide for implementing a research program that addresses high priority needs of the Nation relating to its drinking water and wastewater infrastructure. By identifying these critical needs through an inclusive process with internal and external stakeholders, ORD can select technology research, development and demonstration projects for resource investment and can play a national and international leadership role by cooperating and collaborating with its federal, national and international research partners.

Background

In 2002, the 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. In September 2002, the Agency 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.

In the report, the Agency estimated that if spending for capital investment and operations and maintenance (O&M) remained at current levels, the potential gap in funding for the years 2000 through 2019 would be approximately $270 billion for wastewater infrastructure and $263 billion for drinking water infrastructure[2].

In an introduction to the Gap Analysis report, the Assistant Administrator for Water stated, "While much of the projected gap is the product of deferred maintenance, inadequate capital replacement, and a generally aging infrastructure, it is in part a consequence of future trends we

[2] The analysis estimated a 20-year capital gap for clean water of $122 billion ($6 billion per year) in 2001 dollars. For drinking water, we estimated a capital gap of $102 billion ($5 billion per year). The O&M gaps for clean water and drinking water were estimated at $148 billion ($7 billion per year) and $161 billion ($8 billion per year), respectively. The report also estimated the capital and O&M gaps under a "revenue growth" scenario whereby spending levels by the water industry are projected to increase at a real rate of 3 percent per year, which is consistent with the economic growth forecast in the President's budget. Under the growth scenario, the capital gaps for clean water and drinking water were $21 billion and $45 billion, respectively.

can anticipate today, such as continuing population growth and development pressures. Yet, funding gaps need not be inevitable. They will only occur if capital and operations and maintenance spending and practices remain unchanged from present levels."

The *Gap Analysis* report and other work have helped focus more attention on the importance of sustainable water infrastructure. EPA has acknowledged that some communities may have a difficult time meeting future water infrastructure challenges. However, EPA also realizes that a much bigger challenge is changing how the Nation views, values, manages and invests in its water infrastructure. EPA's Sustainable Water Infrastructure Initiative (SI) acknowledges that through the use of effective and innovative approaches and technologies, a commitment to long-term stewardship of our water infrastructure, and collaboration with all key stakeholders, we can make better use of our resources, potentially reduce the funding gap and move the Nation's water infrastructure down a pathway toward sustainability. This is clearly stated in the SI vision statement:

> We will collaborate with our external stakeholders and, through research and development, seek innovative approaches and new technologies to help ensure that the Nation's water infrastructure is sustainable through better management and operations, improvements in water efficiency, full cost pricing of water supply and wastewater treatment, and watershed-based approaches to solving water quality and water quantity problems.

The Agency views its primary role as that of an advocate for sustainable water infrastructure. Led by the Office of Water and supported by many other Program Offices and the Regions, SI represents a collaboration with public and private utilities and municipal governments that provide drinking water and wastewater services; state and tribal water and wastewater programs; drinking water and wastewater equipment manufacturers and consultants; academia; and environmental advocacy groups.

The Office of Water has taken the leadership role in implementing SI and is relying on key support from other EPA Program Offices and Regions, especially ORD, which can provide critical support in identifying new and innovative approaches and technologies, and in transferring the results of its research in a form most useful to the wide range of stakeholders.

While the Agency has initiated SI to focus its efforts on addressing the needs of the Nation's water infrastructure, there is an emerging movement within the drinking water and wastewater industry towards the adoption of comprehensive asset management. A recent U.S. Government Accountability Office (GAO) report recognizes that utilities that have started adopting comprehensive asset management are reporting several beneficial aspects to their operations. In particular, by collecting, sharing, and analyzing data and information on their capital infrastructure assets, utilities are allocating their resources more effectively and making better decisions on the level of investigation needed and whether to rehabilitate or replace aging assets. (GAO, 2004)

The Agency recognizes the value of comprehensive asset management and OW currently sponsors many initiatives that encourage its application by water utilities through partnerships with industry associations, state and university-based training programs, and the establishment of technical assistance centers. Clearly, drinking water and wastewater utilities are beginning an "asset management paradigm shift" and this research plan has been developed recognizing the changing nature of water infrastructure management.

ORD has long recognized the need for research and development in the area of drinking water and wastewater infrastructure. Most recently, during the summer of 2005, in support of the Agency's SI 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 and Safe Drinking Water Act requirements. This research program recognizes that an essential component of planning for water infrastructure is incorporating security aspects. Thus, the program will coordinate with the water security program at the National Homeland Security Research Center.

The program will be based on a public-private research approach and will be conducted in cooperation with key stakeholders to ensure that outputs meet users' needs, and to optimize collaboration and technology transfer. ORD is best suited to provide the overall leadership of this research program. This recognition is based on ORD's mission, breadth of perspective, impartiality, objectivity, experience, and scientific and technical capability. A renewed ORD presence in water infrastructure research will serve as a catalyst for innovation and will enhance the opportunities for collaboration and leveraging with relevant Federal and international research programs, states, academia, and utilities.

In the 2005 research proposal, two major program areas were identified. The first was "Better Management of Existing Wastewater Collection System Infrastructure" and includes the following:

- Research and evaluation of inspection, condition assessment, and cost estimating tools for existing collection systems to: enable more optimized repair, rehabilitation, and replacement scheduling and budgeting; extend the service life of installed wastewater infrastructure; reduce failures and their adverse public health, collateral damage, economic, and other effects; and foster improvements in precision repair and rehabilitation equipment and procedures
- Research and evaluation of performance and cost of innovative repair, rehabilitation, and replacement technologies and procedures for wastewater collection systems to expand and accelerate the technical options and data available for utilities to select optimal, timely, efficient, and durable repair, rehabilitation, and replacement for deteriorating wastewater infrastructure
- Investigation of advanced design concepts for wastewater collection systems such as real-time control options and advanced drainage concepts (e.g., upland attenuation before sewer system entry) that reduce construction costs and increase carrying capacity and storage capabilities
- Evaluation of novel techniques to improve performance and extend service life of existing systems by addressing problems associated with factors such as: sediments; fats, oils, and grease; pH; corrosion, etc.
- Limited full-scale demonstration of most promising technologies and techniques

The second program area was "Increasing Water Efficiency in Drinking Water Distribution Systems" and includes the following:

- Research and evaluation of innovative approaches to detect, locate, characterize, and repair leakage in distribution systems to conserve source water, reduce capital and operating costs, and reduce contaminant intrusion potential during low pressure conditions
- Research and evaluation of innovative approaches to inspect and assess the condition of high risk water mains to enable more optimized repair, rehabilitation, and replacement scheduling and budgeting; extend the service life of installed drinking water mains; reduce failures and their adverse public health, collateral damage, economic, and other effects; and foster improvements in precision repair and rehabilitation equipment and procedures
- Limited full-scale demonstration of the most promising technologies and approaches

Research Issues

As this plan has been developed, research issues have emerged that reflect the current technical challenges that face drinking water and wastewater utilities. These challenges have also driven

the Agency to launch and implement its SI program, as described earlier. In addition, the general move of utilities towards the use of comprehensive asset management is transforming infrastructure management and will impact the application of innovative technologies and techniques that will emerge from this program.

The research issues presented in this plan have evolved into four major areas. These areas generally conform to and support comprehensive asset management. The research issue areas are condition assessment; system rehabilitation; advanced concepts; and emerging and innovative treatment technologies for wastewater and water reuse.

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

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 drinking water distribution or 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 advanced concepts relating to 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.

Innovative treatment technologies for wastewater and water reuse address the dynamic requirements for improved water quality and the growing demands for safe and reliable reclaimed wastewater and stormwater. The need for more cost-effective wastewater treatment technologies is being driven by many factors. There is a growing challenge to more effectively manage and treat peak wet weather flows at wastewater treatment plants, especially focusing on the effectiveness of pathogen reduction. New and emerging contaminants, such as endocrine

disrupting compounds (EDCs), pharmaceuticals and personal care products, present challenges not only relating to their fate through a wastewater treatment plant, but to their potential capacity to interfere and inhibit treatment effectiveness. The control of nitrogen and phosphorus is a growing priority, especially in the basins that drain to the Mississippi River, Great Lakes and the Chesapeake Bay. There is an ever present demand for wastewater treatment technologies that are more energy efficient and produce smaller volumes of residuals. The use of reclaimed wastewater and stormwater is increasing at a rapid pace around the country, especially in the arid Southwest, California and Florida. Depending on the nature of the "source" water and the intended reuse application, treatment requirements may exceed tertiary levels and demand the use of advanced filtration and membrane technologies.

Partnership Research Organizations

The development of this plan included the participation of several research organizations that are actively involved in a wide range of programs relating to drinking water and wastewater infrastructure, and many other related water resources and water quality issues. These organizations represent national and international research interests, as well as many academic institutions. The following are brief descriptions of the research organizations engaged in the development of this plan:

Water Environmental Research Foundation (WERF) – This organization is the research arm of the Water Environment Federation (WEF), a not-for-profit technical and educational organization with members from varied disciplines who work toward the preservation and enhancement of the global water environment. Formerly known as the Water Pollution Control Association, WEF is the leading professional organization representing the interests of the wastewater collection and treatment industry. WERF manages water quality research through a public-private partnership between municipal utilities, corporations, academia, industry, and the federal government. WERF has a research portfolio valued at nearly $60 million with more than 200 completed and ongoing research projects. WERF research supports more than 250 subscribers, including local municipal wastewater and stormwater agencies in 40 states representing nearly 70 percent of the sewered U.S. population and several agencies in other countries. WERF typically funds nearly $7 million in new projects each year.

American Water Works Association Research Foundation (AwwaRF) – This organization is the research arm of the American Water Works Association (AWWA), an international nonprofit scientific and educational society dedicated to the improvement of drinking water quality and supply. AWWA is the largest organization of water supply professionals in the world. Its more than 57,000 members represent the full spectrum of the water community: treatment plant operators and managers, scientists, environmentalists, manufacturers, academicians, regulators, and others who hold genuine interest in water supply and public health. Membership includes more than 4,700 utilities that supply water to roughly 180 million people in North America. AwwaRF is a member-supported, international, nonprofit organization that sponsors research to enable water utilities, public health agencies, and other professionals to provide safe and affordable drinking water to consumers. AwwaRF is largely funded by member organizations that voluntarily subscribe in order to support and benefit from the water-related research. Almost 900 water utilities and more than 50 water-related consulting firms and manufacturing

companies currently subscribe to AwwaRF. AwwaRF has sponsored more than $370 million in research, represented by more than 600 completed research projects while subscribers provide more than $10 million annually to fund research.

Global Water Research Coalition (GWRC) – Founded in 2002, GWRC is an international water research alliance made up of some of the world's leading water research organizations. GWRC is a non-profit organization that serves as the mechanism for collaborative water research across the globe. GWRC focuses on urban water supply and wastewater issues and renewable water resources, and leverages funding and expertise among the participating research organizations, coordinates research strategies, secures additional funding not available to single research foundations, and actively manages a centralized approach to global water issues. GWRC members are:

- Awwa Research Foundation (United States)
- Cooperative Research Center for Water Quality and Treatment (Australia)
- EAWAG – Swiss Federal Institute for Aquatic Science and Technology (Switzerland)
- Kiwa (Netherlands)
- PUB (Singapore)
- Suez Environmental – International Research Center on Water and Environment-CIRSEE (France)
- Stowa – Foundation for Applied Water Research (Netherlands)
- DVGW TZW – German Waterworks Association - Water Technology Center (Germany)
- United Kingdom Water Industry Research (United Kingdom)
- Anjou Recherche – Veolia Water (France)
- Water Environment Research Foundation (United States)
- Water Research Commission (South Africa)
- WateReuse Foundation (United States)
- Water Services Association of Australia

The U.S. Environmental Protection Agency is the first partner of the GWRC. A partnership agreement was signed in July 2003.

U.S. Department of Transportation, Pipeline and Hazardous Materials Safety Administration (PHMSA), Office of Pipeline Safety (OPS) - OPS conducts and supports research to support PHMSA regulatory and enforcement activities and to provide the technical and analytical support for planning, evaluating, and implementing the OPS programs. OPS sponsors research and development projects focused on providing near-term solutions that will increase the safety, cleanliness, and reliability of the Nation's oil, gas and hazardous materials pipeline systems. Recent R&D projects are focused on, leak detection; detection of mechanical damage; damage prevention; improved pipeline system controls, monitoring, and operations; and, improvements in pipeline materials. These projects are addressing technological solutions that can quickly be implemented to improve pipeline safety.

National Research Council Canada, Institute for Research in Construction (NRC-IRC) – NRC-IRC is the leading construction research agency in Canada. Equipped with world-class facilities, NRC-IRC carries out applied and contract research on issues of strategic importance to the Canadian construction sector. Through an integrated, multidisciplinary approach, NRC-IRC assists the sector to become more competitive through innovation and to foster the provision of safe and sustainable built environments. NRC-IRC's Urban Infrastructure Research Program develops technologies for the design and rehabilitation of infrastructure systems, and innovative tools and techniques for the evaluation and management of these systems. The research focuses on buried utilities, urban roads and concrete structures and sustainable infrastructure for water and wastewater systems.

University Research Organizations – Several universities conducting research and development in the areas of drinking water and wastewater infrastructure have participated in activities leading to the development of this plan. Examples include:

- Penn State University, Pipeline Infrastructure Research Center
- University of Houston, Center for Innovative Grouting Materials and Technology
- Louisiana Tech University, Trenchless Technology Center
- Polytechnic University of New York, Department of Civil Engineering

Evaluation Criteria

In formulating this plan, criteria were developed to guide the evaluation and selection of the programmatic areas in which to conduct research. As mentioned above, the overall goal of this research plan is to generally support the Agency's efforts to address the wide range of problems and issues relating to the Nation's aging water infrastructure. While it is a given that research programs and projects conducted as a result of this plan will support sustainable water infrastructure, more discriminating selection criteria were needed to make program and project prioritization and investment decisions.

The following criteria are based on strategic directions set in plans established at the Agency, ORD and national laboratory levels. These plans set environmental and institutional goals to

guide our organizations and professional staff. For this ORD research plan, these goals have been translated into selection and evaluation criteria.

- Client and Stakeholder Needs: The program or project meets specific needs articulated by clients and stakeholders.
- Cost Effectiveness: The program or project leads to innovations in management, science, or technology that provide added value (i.e., overall, long-term benefits of implementation exceed costs).
- Programmatic Impact: The program has the potential to produce significant, measurable outcomes supporting environmental goals.
- Collaboration: The program or project can be conducted in collaboration and cooperation with other research and stakeholder groups.
- National Leadership and Visibility: The program or project exhibits national leadership within the Agency and with external research and stakeholder groups.
- Technical Expertise: The program or project builds on existing ORD technical capabilities or, through its conduct, helps to develop new capabilities.

Program Guidance and Outcomes

It will be very important to the success of this research program to develop program guidance and outcome measures. Several internal and external stakeholders suggested that we further develop and apply criteria through infrastructure assessments to help refine our research priorities and infrastructure research needs. Within research areas identified in this plan, these criteria will help further delineate research priorities by providing insights into which infrastructure assets and systems may be most vulnerable to high risk failures. It is planned that assessments of water infrastructure will be conducted on national and regional levels. For example, if a predominance of wastewater force mains overlay sensitive groundwater resources and these force mains are identified to be highly susceptible to failure, then these types of assets would be addressed early in the program. Some example criteria for these assessments could include:

- Systems experiencing high growth
- The age of systems and assets
- Local geological conditions, including earthquake prone areas
- Proximity to sensitive ecological systems
- Systems with the potential to affect bathing beaches or shellfish beds
- Infrastructure assets particularly prone to rising sea levels
- Systems that affect sensitive water cycles

Early in the program, we will expedite the development and application of these types of assessment criteria. The results of this effort will provide further insights into the nature of the

challenges that our aging and deteriorating water infrastructure present. As mentioned above, it is expected that this effort will provide information that will help develop national assessments and will provide more regionally focused assessment information. For example, an assessment of the most critically important water infrastructure in our coastal regions will provide direction to our research program as well as internal and external stakeholders responsible for the protection of our valuable coastal resources and the health of those enjoying those resources.

The application of these types of criteria and the conduct of assessments will also support the definition of outcome measures and accountability for the program. When program priorities are established and refined as mentioned above, outcome measures that can be used to gauge program accountability will naturally follow. For example, an outcome of this program could be a measurable reduction of wastewater force main failures and resultant decrease in the incidence of contamination of water resources. These accountability measures could relate to both programmatic and project level outcome tracking. These outcome measures could include:

- Reducing of life-cycle costs for water infrastructure management
- Extending service life of installed infrastructure
- Reducing sewer overflows, back-ups, failures
- Reducing I&I and peak wet weather flows to treatment plants
- Reducing high risk water main breaks
- Improving condition assessment and decision-making capabilities
- Reducing potable water leakage and intrusion potential
- Increased adoption of asset management and the use of performance and cost data for decision support
- Increasing the adoption of innovative technologies

As program implementation begins and national and regional assessments are conducted, a suite of key outcome measures which will provide feedback on the success of the program will be identified. In addition, project specific outcome measures will be developed for each project. To the extent possible, outcome measures will be built on data and information currently collected and available. This will allow comparison of program progress and project results with historical trends. For those outcome measures for which historical information may be lacking, baseline data will be collected against which program and project results will be compared. It is anticipated that as the program matures, experience with the development and deployment of outcome measures will improve, leading to more effective and efficient reporting of progress.

References

U.S. Environmental Protection Agency. 2006a. Innovation and Research for Water Infrastructure for the 21st Century – EPA Research Planning Workshop – Draft Meeting Report, March.

U.S. Environmental Protection Agency. 2006b. Innovation and Research for Water Infrastructure for the 21st Century – Water and Wastewater Infrastructure Draft Research Issues Report, June.

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.

Condition Assessment of Wastewater Collection Systems

Background

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)

The focus of sewer system condition assessment and rehabilitation on the reduction of I&I, almost exclusively targeted excessive hydraulic loading in collection systems and at treatment facilities to lower capital and operation and maintenance costs, and to prolong the lifetime-capacity of the treatment facility. (EPA, 1991) 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, comprehensive asset management is broadening the focus of sewer system condition assessment. In addition to condition assessment that seeks to determine excessive hydraulic loading and I&I, currently practiced comprehensive asset management assesses the likelihood that a capital infrastructure will deteriorate and potentially fail, and the consequences of that deterioration and failure in terms of costs and effect on the system's ability to deliver desired services and meet performance measures. (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.

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 into innovative inspection technologies and condition assessment methods that address corrosion-related wastewater infrastructure issues.

Deteriorating collection systems can result in excessive infiltration of rising ground water during high water table seasons and wet-weather events, and the export of recharge water from watersheds. When this is combined with increased impervious surfaces and water withdrawals resulting from urban growth, the effect of these man-made influences on the natural water balance can result in reduced flows in streams affecting aquatic ecosystems and decreased water availability. The application of isotope hydrology could provide innovative assessment

techniques to determine relationships between aging infrastructure and altered water balances, leading to measures to reduce or mitigate resulting adverse consequences.

Force mains are a relatively small, but important, segment of the wastewater collection system infrastructure. Force mains convey pumped sewage. There are about 30,000 miles of force mains in the nation. Based on a sewer pipe inventory of approximately 600,000 miles, force mains comprise about 5% of the total, by length. Because of hydrogen sulfide generation in wastewater collection systems, force mains are more prone than drinking water pipes to corrosion at the crown of the pipe. The average length of force mains is around 3600 ft. About 60% of the total length of force mains is constructed of ferrous materials, with ductile iron being the dominant material. A significant percentage of ductile iron installed has an internal lining that is most commonly cement mortar. For diameters of 36 inches and greater, pre-stressed concrete cylinder pipe (PCCP) and concrete cylinder pipe (CCP) are the dominant types. For diameters up to 20 inches, asbestos cement has a small but not insignificant percentage. For diameters less than 12 inches, polyvinyl chloride (PVC) and polyethylene (PE) account for about a third of the length installed. Most force mains are in constant service and cannot be accessed internally for inspection without expensive by-passing arrangements.

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 ASCE and WEF on monitoring systems and physical security enhancements, including security measures for wastewater collection systems. This program will coordinate with EPA's Water Security Division and National Homeland Security Research Laboratory to leverage resources, identify collaboration opportunities, and assist wastewater utilities in developing and implementing comprehensive inspection and condition assessment programs.

State of the Technology

The ability to visually examine the internal condition of a gravity sewer using internal cameras, usually 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) In addition, the National Association of Sewer Service Companies (NASSCO) provides a wide range of training programs that is attempting to standardize the application of condition assessment techniques. NASSCO's programs address the assessment of sewer pipe, manholes and service laterals.

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 limit this issue, 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 currently being used 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 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 could be generated in the early phases of this research program. Wastewater utilities that are well known for their innovative application of CCTV could 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 issues meeting (EPA, 2006a) and the expanded research issues evaluation conducted to develop the research issues report (EPA, 2006b). 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, including force mains and service laterals, 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 the impact of deteriorating collection systems on urban water budgets be developed?
- Can the dynamics of wastewater collection system infrastructure failure be better understood, diagnosed, and learned from 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 proposed. Each proposal indicates the estimate time frame for the work. While these proposals address the issues in the questions above, modified, alternative or additional projects may evolve as this plan is implemented.

1. **Technology Transfer Product: Optimization of Internal Camera Inspection Data and Information for Effective Condition Assessment –** A comprehensive evaluation of the state of the art of internal camera inspection of wastewater collection systems. (12-15 months)
2. **Technology Demonstration/Verification Program: Emerging and Innovative Technologies for the Inspection of Wastewater Collection Systems** – An inspection technology demonstration/verification program, conducted in cooperation with wastewater utilities and other research organizations. In 2004, WERF published a report titled, "An Examination of Innovative Methods Used in the Inspection of Wastewater Systems," which identified many innovative inspection technologies that were emerging to support collection system condition assessment. This demonstration/verification program will be a collaboration between EPA, other research organizations, and wastewater utilities, to gather technically reliable cost and performance data during applications of these technologies in a wide range of field conditions. (48-60 months)

3. **Applied Research Review and Evaluation: Understanding the Forensics of Sewer Failures to Support Failure Forecasting Model Development** – A comprehensive review of the research literature to determine our understanding of the critical factors that cause sewer system failures and an evaluation of current ability to conduct forensic studies of sewer failures to enhance our ability to model and forecast future failures to support risk assessments. This effort will be conducted in close collaboration with related work under condition assessment for drinking water distribution systems. (36-48 months)

4. **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. This program could be a cooperative effort with other Federal departments, such as the Department of Transportation's Office of Pipeline Safety, to identify these technologies, assess their transferability to drinking water and wastewater applications, and support technology development. (24-36 months)

5. **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. (24-36 months)

6. **Innovative Condition Investigation Method Development: Identification and Evaluation of Urban Water Balance Impacts Due to Deteriorating Collection Systems** – The exploration of using isotope hydrology techniques to identify and evaluate the effects of deteriorating collection systems on urban water budgets. (24-36 months)

7. **Technology Application Methodology Development: Asset Management Guidance and Tools** – Guidance and tools for assisting wastewater utilities in applying inspection and condition assessment technologies in support of asset management decision-making. This will include a tool for prioritizing sewer inspections, selecting the appropriate technology and inspection technique, and establishing inspection frequency based on a risk-based methodology. Currently applied approaches, including the WERF's SCRAPS (Sewer Cataloging, Retrieval, and Prioritization System) and Seattle Public Utilities" Sewer Pipe Risk Model will be evaluated and further enhanced to develop a "next generation" approach. (18-60 months)

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Condition Assessment of Water Distribution Systems

Background

This portion of the research plan addresses condition assessment of drinking water transmission and distribution mains. Condition assessment is the collection of data and information through direct and/or indirect methods, followed by analysis of the data and information, to make a determination of the current and/or future structural, water quality, and hydraulic status of the pipeline. Where it is applicable and cost-effective, condition assessment is a vital component in effective water infrastructure asset management. A good understanding of pipeline condition can help a utility to optimize operations, maintenance, and capital improvement decisions. This helps to reduce structural, water quality, and hydraulic failures and their adverse effects, and to minimize life-cycle costs. However, condition assessment may also be technically and/or economically infeasible in many cases, and it may be preferable to perform reactive or scheduled maintenance, rather than condition-based maintenance. Therefore, the ability to rapidly, thoroughly, and objectively assess and rank condition assessment versus alternative approaches for a range of pipe materials and failure mechanisms is also very important for its efficient development and use.

The primary research emphasis in this program will be structural condition assessment, as opposed to hydraulic or water quality condition assessment. Structural condition of the pipeline is narrowly defined here as the presence/absence of holes, cracks, breaks, or conditions leading to their formation, in the transmission or distribution pipe wall, lining, coating, and joints. Structural condition does not, as defined here, generally include occlusion of the pipe bore by tuberculation, scale, or other deposits. Structural condition assessment involves: (1) development of a formal or informal structural-condition-rating approach that links pipeline parameter data to the likelihood of structural failure (i.e., holes, cracks, and breaks) for the time period of interest; (2) collection of data (e.g., physical, environmental, and operational characteristics; failure history, processes, and associated indicators) by applicable direct and/or indirect methods, necessary to characterize the pipeline's current and future structural integrity; and, (3) analysis of the pipeline data and information to categorize pipe structural condition, based on the structural condition rating approach, as to its likelihood of failure for the pipeline sections and time periods of interest. The structural condition assessment results are used as input to an informal or formal decision-support system. The decision support system considers not only condition assessment results, but also other factors (e.g., consequences of failure, available options and their cost, level of service targets, and hydraulic and water quality conditions, etc.) to determine whether, when, where, and/or how the pipeline should be inspected in greater detail, repaired, rehabilitated, replaced, or whether operating conditions (e.g., pressure, flow control, or corrosion protection) should be changed.

The demand for, and value from, cost-effective structural condition assessment of moderate-risk and high-risk pipes should increase significantly over the next 20+ years. Pipes installed during construction booms in the 1920s and 30s as well as the post WWII boom are likely to begin to fail en masse, and the ability to determine pipe condition will enable the worst-condition pipes to be addressed first, which helps minimize failures and associated risks, damages, and costs. It will also help avoid premature replacement of sound pipe, which will save resources and time.

The annual replacement rate is projected to peak around 2035 at about 2% (i.e., 16,000 to 20,000 miles of pipe replaced/year), which is more than four times the current replacement rate. (U.S. EPA, 2002 a and b). The sooner that useful, cost-effective structural condition assessment devices and procedures are developed and brought into common use for supporting water infrastructure decision-making, the greater the benefit to drinking water utilities and their customers.

It's difficult to precisely inventory water mains, due to the time and cost involved, but a 2004 estimate (U.S. EPA, 2007) is approximately 1,000,000 miles of water mains in the United States. About 57 % of drinking water mains are made of ferrous materials, with lined and unlined grey cast iron mains representing nearly 29 % of the total, ductile iron (predominantly cement-lined) about 24%, and steel (both unlined and cement-lined) about 4%. Other significant materials include polyvinyl chloride (PVC) (17 %)[3], asbestos cement pipe (15%), prestressed concrete cylinder pipe (PCCP) (2%), and polyethylene (1%). About 6% of the pipe materials were either used in < 1% of total length of mains or the material type was unknown/unreported. A 1994 estimate (U.S. EPA, 2007), indicates that new systems were most commonly installing ductile iron pipe (48%), and PVC pipe (38%), and the total annual rate of expansion was 13,200 mi/yr.

Because of the range of pipe materials and failure modes, there are differing characteristics and defects that often require specific investigation approaches. One common defect for all types of pipe is leakage through the pipe wall, joints, or connections, which can not only release water or allow intrusion during low-pressure events, but can also lead to soil erosion and loss of support. Even leakage investigation approaches need to be tailored to differences, for example, in leakage volume and rate or in sound attenuation due to pipe diameter, pressure, materials, or backfill. Particular needs in assessing ferrous pipe include: the condition of pipe wall and joints (specifically external and internal corrosion, pitting, graphitization and fractures), and the condition of internal lining. Particular needs in assessing prestressed concrete cylinder pipe (PCCP) (e.g., lined cylinder pipe (LCP) and embedded cylinder pipe (ECP)) include: detection of wire breakage arising from corrosion, embrittlement or excessive pressure, and corrosion of joints. Particular needs in assessing flexible plastic pipe include: detection of deformation and material degradation. Particular needs in assessing asbestos cement pipes include: detecting abrasion and decomposition of the pipe wall.

The user community strongly desires that condition assessment approaches should be non-disruptive, i.e., they don't require excavation, de-watering, or entry into the pipeline. Non-disruptive technologies provide not only economic and customer convenience benefits, but they also reduce the risk of entry of contaminants or of dislodging sediments, biofilm, or tuberculation already in the system.

In order to effectively assess the structural condition of a pipeline, reliable correlations must exist and be recognized between data and information that can be collected about the pipeline, and its structural integrity status. Much progress has already been made in this area, but a better

[3] Based on personal communication with Robert Walker of the Uni-Bell PVC Pipe Assocation, who cited a confidential industry study, the length of PVC pipe installed in rural systems is seriously undercounted in the distribution system inventory cited above. The industry study estimates that the actual miles of PVC installed are many times greater than the estimate above.

understanding of the correlation between measurable data and information will improve the understanding of the range of situations where condition assessment can or cannot be applied. Since many water transmission and distribution pipelines have been successfully designed, manufactured, installed, and operated up to, or beyond, their design service lives, the relevant structural integrity factors and associated safety margins for new pipelines are often being effectively addressed. On the other hand, there are an estimated 240,000 main breaks/year), and a portion of these are catastrophic, which indicates that the technical and/or economic feasibility of measuring the right parameters, and/or the ability to interpret the data, are not adequate for high-risk mains.

The scope and goals for structural condition assessment can vary substantially, and they strongly influence the type, quantity, quality, and cost of acquiring and analyzing the data required to complete the assessment. Three examples follow that illustrate a range of combinations of scopes and goals. Example Scope and Goal 1: Establish a preliminary investment plan for future replacement of a class of pipe in similar environmental and operating conditions. In this case limited pipeline data (e.g. installation date, and characteristics of pipe, soil, and climate), plus service life history or deterioration curves from similar pipelines in similar settings, would be sufficient condition data to support this goal. Example Scope and Goal 2: Economically and promptly detect and locate potentially serious deterioration during operation of a prestressed concrete cylinder pipeline (PCCP). A potential option for meeting this goal would be minimally invasive acoustic emission monitoring to detect the number and location of prestressed wire breaks. Example Scope and Goal 3: Make a final decision about the correct option (i.e., no action, repair, rehabilitation, or replacement) for the potential problem areas identified in Example 2. Achieving this goal may require de-watering and/or excavating the pipe at the locations identified during acoustic emission screening, followed by detailed direct inspections by destructive or non-destructive methods.

Condition assessment depends on the quantity, quality, and availability of data, and three broad approaches were identified at the workshop for improving condition assessment data.

- Improve the consolidation, organization, and use (within and between utilities) of data and information that already exist, but are under-utilized. The data and information are, for example, installation, environmental, operating, and maintenance records, and failure case histories for various types of pipe, environmental, and loading conditions. A desire was expressed for the development of a database for these types of data.
- Improve the acquisition and analysis of additional condition assessment data from existing technologies (e.g., automatic meter reading, SCADA, and statistical analysis). This approach may have important economic advantages, if the new condition assessment data adds value with little additional expense to the utility.
- Improve the type, quality, spatial density, frequency, speed, and economics of pipe condition data acquisition by utilizing new technologies (e.g., sensors, transmitters, data storage, computers, robotics, software). This approach attempts to leverage a broad range of new technologies. The key to acceptance of new technologies will be the physical or logical demonstration of substantial value-added to utilities.

Workshop attendees and research plan reviewers recommend that EPA structural condition assessment research activities for water mains should emphasize a coordinated, collaborative approach. Numerous options already exist for collecting and analyzing condition data for drinking water mains, but these options have limitations, which represent potential research needs. There are a large number of combinations of pipe materials, configurations, and failure modes, and many cannot be adequately or economically characterized by existing structural condition assessment approaches. However, there aren't sufficient resources to address all combinations, so it's important to focus on scenarios of greatest interest to utilities and regulators. Improved technologies must provide value-added for utilities and be both technically and economically competitive with alternative approaches. A substantial amount of relevant research, development, testing, and verification (R,D,T,&V) is recently completed, underway or planned by, for example, the American Water Works Association Research Foundation (AwwaRF), the Water Environment Research Foundation (WERF), the Global Water Research Coalition (GWRC), the European Commission (EC), National Research Council Canada (NRCC), and Commonwealth Scientific and Research Organization (CSIRO/Australia). Many structural condition assessment improvement efforts involve applying recent advances in technology (e.g., sensors; probe signal generation; data transmittal, storage, and analysis; and robotics) to the creation of better, cheaper, and faster ways of acquiring and analyzing structural integrity data. It is important not to duplicate this research, and also to take advantage of opportunities for parallel or joint research at desktop-, laboratory-, pilot-, or full-scale. A substantial amount of research, development, testing, and verification (R,D,T,&V) is also completed, underway, or planned for structural condition assessment for non-drinking water applications, such as oil and natural gas pipelines, nuclear power plants, large buildings, bridges, and aircraft. This research may offer potential for technology transfer to the water sector.

As described above, improved condition assessment capability has potential for improving structural asset management for water infrastructure, but it also has limitations, and there are difficult challenges to overcome.

- One limitation of condition assessment is that it does not, and is not likely to, produce a precisely accurate prediction of the time and location of failure. Pipe structural failure occurs when the loading on the pipe exceeds the ability of the pipe to resist it. There are a range of types and magnitudes of environmental conditions and loadings acting on the pipe, so predicting exactly when and where the pipe will fail is very difficult. Also, as a pipe deteriorates, failure may be triggered by smaller loads that would have been resisted earlier in the pipe's lifetime, and this strength deterioration adds to the difficulty of predicting time and location of failure. If the time and location of failure prediction are not exact, then it becomes more difficult to quantify the value of condition assessment. Nonetheless, if condition assessment can be conducted more frequently and accurately because of technology performance and/or cost improvements, it should enhance the capability of tracking pipe deterioration, and the approach toward conditions that pose an unacceptable probability of failure.
- Cost is a very important consideration, and condition assessment is not economically feasible for all situations. For example, for low-risk mains, the cost of condition assessment may exceed the value of any damages prevented following failure. So, for low-risk pipes, it may be better to repair after failure, and replace when the failure rate

becomes unacceptable based on economics or service reliability considerations. For moderate- and high-risk mains, there should be a greater willingness to pay for structural condition assessment, but a structural condition assessment approach that far exceeds its benefits is not likely to be widely used. On the other hand, if dramatic reductions occur in inspection and rehabilitation costs, this will have a favorable influence the economic feasibility of inspection.

- Some types of failures may not be preventable through more intensive structural condition assessment. For example: the critical failure mechanisms and conditions may be poorly understood; the failure mechanisms may provide too little pre-failure warning to enable preventive action; or, the critical parameters may be technically or economically infeasible to monitor.
- Documenting long-term value-added and reduced life-cycle costs for utilities will require some long-term studies. For example, if condition assessment indicates that a pipeline can be safely operated 10-yr longer than previously planned, it won't be known if the prediction is actually correct for 10-yr. Surrogate measures, e.g., measure deterioration, laboratory tests, modeling can be used to estimate accuracy of projections in a shorter time period.

It will be important to keep these challenges and limitations in mind during project selection and project and program progress reviews in order to focus on projects with good prospects for providing value-added to utility asset managers.

State of the Technology

Indirect assessment: A great deal can be learned about the potential for defects in the system from: (a) historical data such as the age of pipe, manufacturer, when and who laid it, and experience of various pipe materials; (b) environmental data such as soil conditions, ground water tables, surface conditions; and (c) operational data such as flow, maintenance and repair records. This information, from which pipe and/or network condition can be inferred, coupled with information about potential consequences of failure, is of great value in focussing an investigation strategy to those sections in most need of assessment. Indirect methods are generally less costly than direct methods. Indirect methods may not provide the level of detail, timeliness, or confidence required for maintenance and renewal decisions about pipes with a high consequence of failure. A number of decision support tools have been developed for prioritizing investment, maintenance, and replacement schedules, e.g., Deb et al., 1998; Deb, et al., 2002a; Deb et al., 2002b; Kleiner et al., 2005; O'Day, et al., 1986; Sagrov, 2003; Sagrov, 2005; Stone et al., 2002; WERF, 2004. Evaluating the practicality and value of innovative decision support tools will assist the user community to select appropriate options.

Direct Assessment: Direct methods include visual inspection, destructive methods, and nondestructive methods. Visual inspection may be done in-person for larger diameter pipes or the exterior of excavated pipes, or it may done by closed-circuit TV (CCTV) for the interior of a wide range of pipe sizes. CCTV is used for both water main and force main inspections. CCTV can be beneficial, but it inspects only the inner wall of the pipe, not wall thickness, the outer wall, and pipe bedding voids. Destructive testing involves pipe coupon sampling (i.e. removal of

a sample of the pipe wall) and analysis for thickness, defects, damage, and residual strength. Hydrostatic testing (i.e. isolating pipe, filling, pressurizing, then observing pressure or fluid loss) is a nondestructive evaluation except in cases where pressurizing the pipe causes failure at weak spots. Hydrostatic testing is the most common (i.e., 20% of surveyed utilities) investigation method for sewer force mains among surveyed utilities.

Nondestructive testing (NDT) methods measure various structural parameters without damaging the inspected material. Evaluation and improvement of NDT methods for a range of water and wastewater pipe scenarios has attracted considerable attention (e.g., Jackson et al., 1992; Hunaidi et al., 1999; Mergelas and Kong, 2001; Dingus et al., 2002; Lilley et al., 2004; Reed et al., 2004; Thomson et al., 2004).

- NDT methods available for pipes include penetrant testing for cracks (not common for water pipes), x-ray inspection (not common for water pipes), acoustic emissions (e.g., for wire break events in PCCP), acoustic leak detection, remote field eddy current (for ferrous pipe), remote field eddy current/transformer coupled (for broken wires in PCCP), magnetic flux leakage (mostly for steel pipe), ultrasonic pulse velocity (for wall thickness measurement), ultrasonic guided waves (primarily for pipe with welded steel joints) , and seismic methods (for PCCP defects).
- Except for acoustic leak detection and location, and acoustic wire break detection for PCCP, NDT for pressure pipes is not in widespread use. One estimate is that current NDT technology is only applicable to about 10% of U.S. drinking water mains (Dingus, et al., 2002). Limited use of NDT methods can be attributed to several causes including their high cost, disruptiveness, and for most methods the lack of a track record. Slow development of NDT methods for water pipes may be attributed to small market size, challenging testing conditions in water mains, and/or lack of understanding and consensus regarding the requirements for pipe inspection.
- Current and expected improvements in NDT-related technologies such as sensors (e.g., sensitivity, miniaturization, durability), sensor platforms (e.g., robotics), sensor networking, communications, data interpretation, and computing, indicate that NDT capability, and its applicability to water mains can be substantially improved. Water mains with moderate to high consequences of failure should be the focal point for NDT improvement on the basis of risk reduction potential and economic feasibility.

Recent innovations: A number of innovative and effective new developments have occurred that greatly improved the capability of providing the information needed to make an assessment.

- ***Leak Detection*** – Externally applied leak correlator tools have been in existence for many years, but important advances have been in the development of in-line tools. A hydrophone, either tethered or free, is inserted into an operational main and is moved along by the pressure. The great advantage is that due to closeness of the hydrophone to the leak, it can detect and pinpoint small leaks. The most advanced of these is Sahara, which was developed for the water industry. Smartball is an innovative acoustic acquisition device complete with power supply that is contained within an aluminum casing and then placed inside a foam ball, which can float through the pipes with

diameter > 10-in. and operate up 17 hours. Acoustic detection and recording modules have been developed that can be placed at selected locations to monitor leakage at night for several days or weeks, then the units are either retrieved or queried and the data are analyzed to identify leaks. A leak detection monitoring system using long, acoustic fiber optics is being tested in Arizona. Another innovative system integrates automatic meter reading systems and leak detection.

- ***Ferrous Pipe Investigation*** – Broadband Electro-Magnetic (BEM) is a patented technology developed in Australia that is commercially available. It works by inducing eddy currents to flow in close proximity to a transmitter. These currents migrate with time and the collected data can provide an accurate profile of the pipe wall. It can see through even significant linings and coatings without their removal, which is a major advantage. Another advantage over ultrasonics is that it generates a contour plot of the whole section of pipe. It can detect metal loss to 1/25" of an inch. To scan internally the pipe has to be out of commission and a short section of pipe removed to allow insertion of the BEM pig. BEM operating speed is low. **Remote Field Technology (RFT)** – An RFT tool used in the oil and gas industry is the "See Snake" which is stated to be suitable for pipeline diameters of 2" to 8" and is flexible and able to negotiate bends and captures data and stores it on board. **Magnetic Flux Leakage** – A UK company has developed MFL external inspection tools for small and medium sized ferrous pipe. **Sonics and Ultrasonics** – An ultrasonics in-line intelligent pigs for water and force mains was undertaken by the UK utility Thames Water. This is a prototype and not commercially available. It is believed that there are similar developments underway. **Linear Polarization Resistance (LPR)** – A device developed in Australia utilizes working, counter and reference electrodes using a Ferguson-Nicholas cell. The polarization resistance is used to determine the maximum pitting rate of a ferrous pipe in that type of soil by reference to an established data base. It can be used in the assessment of external corrosion of a ferrous pipeline.
- ***Ferrous and other pipe materials investigation*** – **<u>Acoustics</u> --** A new acoustic technology for measuring the remaining general wall thickness for water pipes has been developed by National Research Council of Canada. This method is non-destructive and does not require taking pipes out of service. The method uses acoustic signals induced in pipes by releasing water from fire hydrants. These signals are measured by acoustic sensors at two points 300 to 600 ft apart along a pipeline. In principle, this new method can be used on all types of pipes including cast and ductile iron, steel, PVC, asbestos cement and PCCP.

Research Questions

1. How can condition assessment decision support approaches be improved?
    a. How can/should procedures be improved for setting pipeline investigation priorities (i.e., determining whether, when, where, and how to assess pipe condition)?
    b. How can/should procedures be improved for utilizing outputs from condition assessment to support asset management decisions?

c. What is the estimated value of, and market for, condition assessment for key pipe scenarios?
d. What existing types of condition assessment information and data could, if collected and made readily available, support better decision-making among the user community (e.g., utilities, inspection/condition assessment service providers, inspection technology manufacturers, researchers, research funding organizations)?
    i. How can the quantity, quality, and accessibility of those data be improved?

2. Can innovative technologies and procedures substantially improve condition-based management of drinking water infrastructure assets?
    a. Can innovative condition assessment technologies and procedures provide more timely and reliable warning of impending failures in high risk mains (e.g., large diameter cast iron, ductile iron, steel, PCCP, asbestos cement) so that a substantial reduction can occur in currently unpreventable catastrophic failures?
    b. Can correlations be substantially improved between measurable structural parameters and pipe condition for key pipe scenarios?
    c. How can the evaluation and acceptance of innovative, improved condition assessment technologies be accelerated?

3. Can condition assessment for key pipe scenarios be improved through better understanding of failure mechanisms and their indicators?

Proposed Drinking Water Pipe Condition Assessment Research

1. **Applied Research: Decision Support Evaluation and Improvement –** A rational decision about whether it is worthwhile to implement or improve condition assessment requires that estimates be made regarding the applicability, technical and economic feasibility, and value of condition assessment for the approach and application under consideration. This project will evaluate and develop procedures and data to support selection decisions for both implementation and research regarding condition assessment for water mains.
    a. **Value of condition assessment –** The value of condition assessment will be assessed and documented from several perspectives. Procedures will be developed, reviewed by the user community and subject experts, and then implemented for quantifying the cost and number of high consequence failures, which will help establish the maximum value of direct condition assessment and/or identify key data gaps. The relationship between the value of the asset and the acceptable cost of investigation, which will assist in determining what might be economically feasible with existing and future condition assessment approaches, will be investigated. The cost-effectiveness of condition assessment on a life-cycle basis will be determined for selected case histories. The breakpoint between reactive vs. condition-based maintenance and between NDT vs. indirect assessment approaches (e.g. use of historical, operational, and environmental data) will be evaluated for high priority scenarios. Optimization of inspection frequency based on a system for establishing risk of failure for water pipes will be investigated. The feasibility will be explored of developing

a condition rating system or scale, e.g., an infrastructure condition factor (ICF) on a scale from 1 to 10 that can be used, together with information about the rate of deterioration, for optimizing the cost of rehab and replacement programs. This effort will build on WERF 03-CTS-20CO – Condition Assessment Protocols, jointly sponsored by WERF, AwwaRF, and EPA, and other relevant research.

b. **Research awareness and priority-setting** – The following products will be generated to help ensure that condition assessment research leverages available knowledge and collaboration opportunities, and meets high priority needs of the user community. An annual review of condition assessment research will be published. A condition assessment research database will be developed that will help foster more efficient collaboration and reduce redundancy. We will participate in updating research roadmaps for key water infrastructure condition assessment needs.

c. **Improving Quantity, Quality, and Accessibility of Condition Assessment Data –** This project will involve working with key stakeholders to develop a condition assessment database for water and wastewater mains that contains information on pipe failures and consequences; inspection procedures, frequencies, results, and costs; and repair, rehabilitation, and renewal methodologies and costs. The database is expected to support more effective selection of pipe, pipe inspection, and pipe rehabilitation methods.

2. **Technology Evaluation and Improvement: Condition Assessment Technology Performance and Cost –** Advances in, for example, sensing, sensor platforms, computing, miniaturization, and communications are potentially enabling improvements in inspection speed, spatial coverage, temporal coverage, failure mode coverage, and cost. Independent performance and cost data for key pipe situations help developers, users, researchers, and research funding organizations to make sound decisions about application and development of innovative inspection devices for more effective and efficient management of drinking water infrastructure.

   a. **Evaluate/demonstrate technologies** - The project will evaluate/ demonstrate innovative approaches for timely, accurate, reliable, and cost-effective detection of pre-failure indicators for high-risk classes of water main breaks.

   b. **Develop technology evaluation protocols and metrics** - The project will also develop protocols and metrics for demonstrating/verifying existing and innovative condition assessment technologies' performance and cost for key pipe situations.

   c. **Improve accessibility for in-line inspection** - To help overcome in-line inspection accessibility problems that limit their application, the project will collaborate with relevant organizations to develop commonly accepted design standards for new distribution system installation for ease of inspection and assessment.

3. **Basic and Applied Research: Causes, Mechanisms and Predictability of Failure to Enhance Condition Assessment Capability** – This project encompasses basic research on pipe failure mechanisms and predictability of unacceptable conditions or ultimate failure, as well as collection and analysis of failure case histories and statistics. This project will be done in close cooperation with utility experts, pipe

manufacturers, consultants, academia, AwwaRF, WERF, U.S. Bureau of Reclamation, CSIRO, GWRC, NRC-Canada, and EU.

a. PCCP -- The project will initially investigate embrittlement of prestressed concrete cylinder pipe (PCCP), which can cause catastrophic failure of large diameter transmission mains. While it is already known that overcurrent in cathodically protected PCCP can cause damage to the prestressing wires, better documentation about the rate of embrittlement and its effect on time to failure will help improve maintenance scheduling, option selection, and failure prevention. The influence of bonding on residual strength of broken pre-stressing wires and the number of broken wires that will cause PCCP failure will be explored. The correlation will be studied between RFEC/TC results and actual prestressing wire damage in PCCP pipe without shorting straps, which seem prone to false positives.
b. Plastic Pipe - The project will develop decay curves and prediction models for estimating performance and remaining life of water mains, including small diameter plastic pipe. Also, the effects of pressure transients on the degradation and failure of plastic pipe will be evaluated.
c. Failure Documentation Guidelines - Guidelines regarding determining and documenting causes of pipe failures will be developed.
d. Predictability and Preventability Indices – The correlation between measurable parameters and probability of failure will be studied for high priority pipe scenarios. Pipe failure predictability and preventability indices for high-priority pipe failure scenarios will be considered and developed where feasible. These indices will quickly indicate to the user, regulatory, and research communities the relative level of difficulty involved in predicting and preventing key types of failures. Changes in the indicators over time will also indicate progress (or lack of it) toward enabling prevention of these types of failures.
e. CI/AC/Polywrapped DI - Pending results of ongoing AwwaRF projects, additional future efforts may be undertaken on predictability and preventability of failures of cast iron pipe bells, asbestos cement pipe, and polywrapped DI.pipe.

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Rehabilitation of Wastewater Collection Systems

Background

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. On a daily basis, significant pipe defects can cause blockages that lead to dry weather sewer overflows and backups into buildings. 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 concrete material and the reinforcing steel, commonly used sewer materials. High rates of infiltration and inflow can lead to sewer overflows, basement backups, significant system capacity issues and excessive peak flows at pumping stations and at the treatment plant. Although an infrequent occurrence, 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. In many cases, these problems are the result of faulty sewer designs. In addition, inadequate inspection, quality assurance and poor construction workmanship 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. Rehabilitated systems can be improved to provide hydraulic conditions and structural integrity better than the original sewer. 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, collapsed, or increased flow capacity is needed, it is usually replaced. Current rehabilitation methods generally address unsound structural conditions. 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
- Root intrusion
- Compromised joint integrity
- Subsequent construction damage

- Groundwater fluctuations
- Poor design and installation
- 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. Pipe age is a factor; however, pipe deterioration is very complex and 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 sound 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 street lateral or main. With current technology, rehabilitating building connections has become technically feasible but, because of the shear number of connections and cost for service renewals, is a significant additional cost. Economics and conditions of service renewals may make this difficult to address systematically. The problem is both critical and sensitive because of legal jurisdiction, private ownership and costs associated with disturbance to the occupant and destruction of valuable landscaping. 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. 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 marginally effective in reducing or eliminating infiltration but will not significantly improve the structural condition and has a limited life-cycle. 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 marginally reduce pipe cross-sectional area and can reduce hydraulic performance, but generally improve the system hydraulics.

Trenchless technologies have moved to the forefront of 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 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 without total surface digging and accompanying traffic and business disruptions.

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 these service laterals.

When performed, rehabilitation of service laterals is generally done by point repair or replacement; cured-in-place lining, 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 (sharp bends/transitions) or the line condition (massive roots).

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 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 ever emerging new materials and methods of construction. 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 plastic materials has replaced in the market the more traditional sewer pipes constructed from concrete, clay and ductile iron. Plastic pipe has and

continues to be an area of innovation 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 becoming standard practice, 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 sewer system rehabilitation have emerged from the research issues meeting (EPA, 2006a) and the expanded research issues evaluation conducted to develop the research issues report (EPA, 2006b). 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, including service laterals, 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 and to allow for easier inspection, maintenance and rehabilitation?
- 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 proposed. Each proposal indicates the estimated time frame for

the work. While these proposals address the issues in the questions above, modified, alternative or additional projects may evolve as this plan is implemented.

1. **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 the conduct of an international technology forum to develop a comprehensive inventory of rehabilitation technologies being applied around the world. This could be conducted in conjunction with the Global Water Research Coalition's Asset Management Work Group. 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. (24-48 months)
2. **Technology Evaluation Report: Sewer Liner Systems** – This will be a retrospective evaluation of liner systems installed in collection systems. This effort will identify key parameters that will be evaluated to determine the performance, durability, and longevity of these systems. This retrospective evaluation will also provide input into potential demonstration and verification protocols rehabilitation technologies. (18-24 months)
3. **State of the Technology Report: Rehabilitation of Service Laterals** – This evaluation report will examine the state of the art in sewer lateral rehabilitation techniques. The special challenges presented by sewer laterals will be identified and innovative rehabilitation approaches will be described. Beyond the technical challenges, the report will include examples of strategies to address legal jurisdictional and private property issues relating to service laterals. (18-24 months)
4. **Technology Demonstration Program: Emerging and Innovative Technologies for Wastewater Collection System Rehabilitation** – A rehabilitation technology demonstration/verification program, conducted in cooperation with wastewater utilities. In 2006, EPA's Office of Wastewater Management published a report titled, "Emerging Technologies for Conveyance Systems – New Installations and Rehabilitation," which identified many innovative inspection technologies that were emerging to support collection system rehabilitation. This demonstration program will be a collaboration between EPA and wastewater utilities, to gather technically reliable cost and performance data during applications of these technologies in a wide range of field conditions. (36-48 months)
5. **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) methods and technologies for 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 improve installation practices and collecting critically needed "as built" information for future rehabilitation decision making. (12-24 months)

6. **Technology Transfer Products: New Materials Evaluation and Collection System Sewer Pipe Selection Guide.** These products will be an evaluation of new sewer pipe materials and 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, emerging 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. (18-48 months)
7. **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 is 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. (24-36 months)
8. **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. (12-24 months)

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Rehabilitation of Water Distribution Systems

Background

When the hydraulic or structural condition of drinking water distribution mains deteriorate, then cleaning, repair, rehabilitation, replacement, and installation of parallel mains are the available options. Pipe rehabilitation is the option predominantly addressed in this research plan. Pipe rehabilitation is done by one of several available lining processes, which are described in more detail below. Pipe rehabilitation has the potential to substantially and economically increase the life of, and improve water quality from, existing pipe infrastructure by reducing corrosion, tuberculation, intrusion potential, leakage, and breaks. It can also reduce energy requirements due to decreased roughness. Pipe rehabilitation/lining is primarily used for unlined ferrous mains, which represent a substantial portion of drinking water transmission and distribution mains. The decision to rehabilitate or replace a pipe is strongly influenced by factors such as the remaining life of the main, the life extension from rehabilitation, the discount rate, replacement unit cost, rehabilitation unit cost, and break repair costs. (O'Day, 1986)

State of the Technology

Rehabilitation by lining involves placing a watertight surface inside an existing pipe. Cleaning is typically needed prior to lining to remove sedimentation, scale, tuberculation, and graphitization. Thorough cleaning is critical to allow for intimate contact of the liner with the pipe. Surface preparation significantly affects the strength and bonding of liners (Ashton et al., 1998). There are three major categories of lining methods based on the structural capabilities and interaction of the lining and the host pipe: nonstructural, semistructural, and fully structural (AWWA, 2001).

- Nonstructural lining involves placing a thin layer of corrosion-resistant material on the inner surface of the pipe. The lining is applied to increase the service life by protecting the inner surface of the pipe from corrosion. It does not increase the structural integrity of the pipe, and does not substantially reduce leakage (AWWA, 2001). The two most common linings for water distribution pipes are cement mortar and epoxy. The cement-based systems depend partly on physical protection due to the lining and partly on the alkaline passivation due to the pH increase caused by the cement. Epoxy systems reduce corrosion by forming a thin, impermeable coating on the inside of the pipe. Nonstructural liners, unlike semistructural and structural liners, do not require excavation to disconnect and re-connect services lines. Nonstructural lining is the most economical option where the host pipe is structurally sound. Recent AwwaRF research projects (Deb et al., 2007 and AwwaRF, 2007) are addressing both epoxy lining and cement mortar lining. Both of these projects are trying to establish a more technical basis for the use of these materials using a combination of experience and laboratory testing. Each project intends to develop an empirical or mechanistic understanding of the deterioration of these materials in different environments, and produce either an equation, look-up tables, or decay curves that can be used to better estimate the projected lifespan of each lining material.
- Semistructural lining involves placing a watertight structure in immediate and interactive contact with the inner surface of a cleaned pipe. "Since the stiffness of such

a lining is less than that of the host pipe, all internal pressure loads are transferred to the host piping, leading to their classification as interactive" (AWWA, 2001). A variety of technologies are available, including: sliplining, close-fit pipe lining, fold and form pipe, and cured-in-place pipe. For semistructural lining, disconnecting and re-connecting services increases excavation and labor costs.

a) In sliplining, the liner pipe is inserted into the host pipe either by pulling with a winch and cable or by pushing with a backhoe or with hydraulic equipment. Before the liner is inserted into the host pipe, individual sections of pipe are fused together to form a single pipe longer than the section to be lined. The annulus between the new pipe and the host pipe is usually filled with grout.
b) Close-fit pipe lining utilizes a continuous pipe that has been deformed temporarily [either by mechanical rolling (rolldown) or by drawing through a reduction die (swagelining)] so that its profile is smaller than the inner diameter of the host pipe. The deformed pipe is inserted into the host pipe and subsequently expanded by applying pressure to form a tight fit against the wall of the original pipe. Annulus grouting is not required as with conventional sliplining.
c) The fold and form lining process utilizes a thermoplastic material (PVC or PE) which is heated and deformed at the factory (from a circular shape to a "U" shape) to produce a net cross-section that can be easily fed into the pipe to be rehabilitated. The fold and form pipe is fed into the existing pipe where hot water or steam is applied until the liner is heated enough to regain its original circular shape and create a snug fit within the host pipe. The liner pipe, fully intact, is then slowly cooled, maintaining the form of the host pipe.
d) Cured-in-place pipe lining involves placing a flexible tube impregnated with a thermosetting resin into a cleaned host pipe using the inversion process. With the aid of hot water or steam, the resin cures and stiffens the tube, forming a new jointless pipe in close contact with the inner wall of the host pipe.

- Structural lining involves placing a self-supporting, watertight structure inside a pipe. Structural lining is typically used in situations requiring minimum disruption to repair structurally unsatisfactory pipe where loss of flow capacity is acceptable. The resultant lining is capable of sustaining the maximum allowable operating pressure of the pipe section being renovated. The structural lining can be either continuous or discrete. For structural lining, disconnecting and re-connecting services increases excavation and labor costs.

(a) The continuous lining approach involves inserting a long section of continuous pipe into the host pipe. The method can cause a significant reduction of the flow area. Plastic pipe is normally used, although steel can be used. Before the liner is pulled into the host pipe, individual sections are fused together. Grouting is typically applied in the annular space between the host pipe and the replacement pipe.
(b) Segmented pipe lining involves forming a new pipe inside the host pipe using split pipe segments. The new pipe is constructed by making longitudinal and circumferential joints of pipe segments. Segmented pipe lining is more common for wastewater pipes. Segmented lining with a steel liner has been done for PCCP drinking water mains (e.g., Kelso, et al., 2006). The steel liner sections have an

unwelded longitudinal seam, and the section is compressed by steel bands to a diameter several inches less than the host PCCP for ease of insertion. After insertion in the PCCP, the bands are cut and the longitudinal seams and circumferential joints are welded. The resultant annular space between the two pipes is grouted. The steel liner also receives a cement mortar lining.

(c) Carbon fiber-epoxy lining has also been used for lining of PCCP. An AwwaRF-U.S Bureau of Reclamation project, starting in 2007 (AwwaRF, 2007b) will seek to develop a standard for use of carbon fiber reinforced polymers (CFRP) as a repair technique for PCCP. This project will develop detailed specifications to ensure use of appropriate materials and techniques for quality PCCP repairs.

(d) The potential of structural spray-on linings will be investigated in a global literature review in an AwwaRF project initiated in 2007. An important advantage of spray-on structural coating is that they significantly reduce the problem of disconnecting and reconnecting service lines. This project will review spray-on structural linings for pipeline rehabilitation, including technologies existing or under development in other countries or industries. A detailed technical assessment of the suitability of these technologies for application in North America will be conducted. Methods of overcoming anticipated difficulties with use of the technologies in North America will be presented.

A number of programs and procedures exist to aid in determining whether to rehabilitate or replace pipe. More data regarding the applicability, effectiveness, and cost of these programs and procedures are of interest to the user community. Infrastructure materials (i.e., pipe, liner, and coating materials) research has been specifically identified by AwwaRF research planning volunteers as an area of work for concentrated focus. In general, all of the projects addressing materials have typically considered: improved understanding of the failure mechanisms, strong and weak applications/characteristics of the materials, and water quality implications of a given material. As indicated above, recent or ongoing projects are addressing epoxy lining and cement-mortar lining of ferrous pipes, and carbon fiber-epoxy lining of PCCP. In 2007 a preliminary investigation (i.e. literature review) of spray-on structural lining is planned by AwwaRF, as well as an assessment of distribution system "optimization" goals that will include structural integrity issues.

Research Questions

The research questions below reflect critical gaps in our knowledge of the performance of innovative rehabilitation technologies, and our ability to determine the most long-term cost effective rehabilitation methods for the situation being addressed.

1. Are decision-making processes for selecting optimal system rehabilitation technologies and methods cost-effective, and do they adequately address relevant factors (e.g., long- and short-term performance and cost , hydraulic effects, structural integrity, condition assessment, maintenance, water quality, consequence of failure)?

2. Can emerging and innovative pressure system rehabilitation technologies, be identified and demonstrated/verified in field settings to improve our understanding of their cost-effectiveness, technical performance and reliability?

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, demonstration and technology transfer products are proposed. These proposals are presented in priority order. Each proposal indicates the time frame for the work.

1. **Applied Research: Rehabilitation vs. Replacement Decision-making**. The capabilities, limitations, benefits, and costs of the principal, existing approaches for determining whether to rehabilitate or replace pressure pipes for representative situations will be identified and characterized. Critical gaps in applicability, performance, data, and affordability will be identified. Case histories on the utilization of rehabilitation vs. replacement decision-making approaches will be collected. A state-of-the-art summary will be produced that will point users to either existing, innovative approaches or to traditional approaches. The feasibility of substantially improving upon existing approaches will also be assessed. Specific recommendations will be made regarding the need for data from accelerated aging tests and case histories.

2. **Technology Demonstration/Verification Program: Emerging and Innovative Technologies for Pressure Pipe Rehabilitation** – A rehabilitation technology demonstration/verification program will be conducted in cooperation with drinking water utilities. This demonstration/verification program will gather technically reliable cost and performance data during applications of these rehabilitation technologies in a range of field conditions. This project will build on and update previous field evaluations of water main rehabilitation technologies (Deb et al., 1999). The initial candidate technology types, based on the EPA research needs workshop, are: structural lining technologies that either avoid digging up service connections, or that greatly reduce the time and effort to disconnect and reconnect services; and, carbon fiber-epoxy lining. A broader survey will be conducted before making the final selection.

3. **Applied Research: Evaluation/improvement of Innovative Repair and Rehabilitation Materials.** This project will complement the demonstration/verification project by generating or collecting data from, for example, laboratory-, pilot-scale testing, or case histories for promising innovative materials. These data will be used in the demonstration/ verification selection process, and will also fill data gaps not addressed by demonstration/verification. Carbon fiber repair patches and liners for PCCP and other pipe applications is a specific technology recommended for further evaluation and improvement at the EPA workshop. There is a need for retrospective evaluation of performance, evaluation of design issues, and development and review of design standards. If carbon fiber is selected for study, the research will be conducted in cooperation with the PCCP users' group, AwwaRF, and US. Bureau of Reclamation.

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Advanced Concepts – Wastewater Collection-Treatment Systems

Background

Stormwater and wastewater collection systems are a critical link in the urban water cycle, especially under wet-weather conditions. In the context of pollution control, these systems transport sanitary wastewater, stormwater, industrial wastewater, irrigation and washwater, and inflow/infiltration (I/I).

Research in the area of collection systems as means of wet-weather pollution control is showing signs of renewed activity, especially in Europe and Japan (Henze et al. 1997, Sieker and Verworn 1996, Ashley 1996, Bally et al. 1996). Case studies of recent applications of innovations in this country are also receiving attention, as evidenced by recent Water Environment Federation technical conferences (WEF 1994a, 1994b, 1995a, 1995, 1996) and a recent EPA seminar (USEPA 1996b). By applying new technology and revisiting traditional urban water problems with a fresh outlook, advances are being made in a wide variety of sewer-related areas. By reviewing successful applications of research in recent projects, a vision of successful wet-weather management of collection systems of the future may be formulated.

A historical review of collection systems in the United States helps with understanding the problems associated with modern sewer collection systems. Many of the early sewers, including some from before the turn of the century, are still in service. As cities grew, the need for stormwater and wastewater conveyance became a necessity to protect human health. Stormwater and sanitary waste were generally conveyed to the nearest natural water body. In fact, the modern word "sewer" is derived from the old English word meaning "seaward" (Gayman 1996).

In the late 19th and early part of the 20th century, these conveyance systems were "intercepted" into a smaller conveyance sized to accommodate a multiple of the estimated dry-weather sanitary flow (Moffa 1990; Foil et al. 1993; Metcalf and Eddy 1914). The first construction of an intercepting sewer for combined sewer systems (CSS) in this country was in Boston in 1876 (Foil et al. 1993). The intercepted sewage was usually transported to a primitive treatment plant consisting of solids and floatables removal via screening and settling (Metcalf and Eddy 1914).

During this period there was considerable debate between proponents of separate systems and those who favored CSS. The appeal of the combined system was one of economics, especially in areas where rainfall intensity was high enough to regularly flush the sewers, greatly alleviating the need for regular cleaning (Metcalf and Eddy 1914). Although engineers in England were strongly advocating separate systems as early as 1842, primarily for sanitation reasons, engineers in America were divided. An important engineering monograph of the time by Dr. Rudolph Hering is quoted in "Design of Sewers" by Metcalf and Eddy (1914):

> The advantages of the combined system over a separate one depend mainly on the following conditions: Where rain-water must be carried off underground from extensive districts, and when new sewers must be built for the purpose, it (combined sewers) will generally be cheaper.

> But more important is the fact that in closely build-up sections, the surface washings from light rains would carry an amount of decomposable matter into the rain-water sewers, which, when it lodges as the flow ceases, will cause a much greater storage of filth than in well-designed combined sewers which have a continuous flow and generally, also, appliances for flushing.

Thus problems associated with settled solids (e.g., maintenance costs and odor problems) were a primary reason for the spread of combined sewers in this country at the turn of the century.

One of the first separate systems designed in this country was in Memphis, TN following a yellow fevcr outbreak in 1873 when more than 2,000 people died. (Metcalf and Eddy 1914; Foil et al. 1993). Separate sewer systems became more widely accepted as receiving water quality decreased and potable water supplies were threatened. They were designed primarily for newer urban areas, but later were also used as a means of doing away whit combined systems. Separate systems, consisting of sanitary and storm sewers, remain the norm in the United States.

However, stormwater pollution has become more of a concern for urban areas (as well as in rural agricultural areas); separate untreated stormwater conveyance is now being questioned as an acceptable design practice. For example, sewer separation, common mitigative action for areas with severe combined sewer overflow (CSO) problems, has been shown in many areas to be an unfeasible solution for reducing water quality impacts. In Cincinnati, OH separation of the combined system was evaluated as a design alternative and shown to be an ineffective means of controlling the total solids load to the receiving water due to the polluted stormwater runoff from the untreated separate storm sewers (Zukovs et al. 1996). In addition, national studies have shown separation to be significantly more costly than other alternatives for CSO pollution control (Field and Struzeski, 1972).

Skokie, IL offers one example of a “new look.” Faced with a massive basement flooding problem caused by combined sewer surcharging, Skokie found traditional sewer separation to be unacceptably costly. Accordingly, controlled and below street storage of stormwater was found to be a cost-effective (one-third the cost of separation) solution. Flow and storage control is achieved with a system of street berms and flow regulators. The premise of this retrofit system, which is almost completely implemented throughout the 8.6-square mile community, is that “out of control” stormwater is the root cause of combined sewer problems. As a side benefit, the Skokie system includes numerous pollutant-trapping sumps (Walesh and Carr 1998).

Problems Commonly Associated with Present Day Collection Systems

As described above, some collection systems in use today in the United States represent over 100 years of Infrastructure investment. During that period the technical knowledge of the nature of wastewater has increased, and the public expectation of the performance and purpose of collection systems has changed. What was considered state-of-the-art pollution control in 1898 is no longer acceptable. The societal goals that the engineer attempts to satisfy with a combination of technical feasibility and judgment has undergone drastic changes in the last 30 years (Harremoes 1997). Present-day collection systems, many of which were designed and constructed in older periods when performance expectations and technical knowledge were less advanced than today, now must perform to today's elevated standards. At the same time, sprawling urban growth has strained infrastructure in many areas, exacerbated by poor cradle-to-grave project management (Harresmoes 1997). Designers of new collection systems must recognize and address the problems of past designs.

The current status of collection system infrastructure in the United States represents a combination of combined, sanitary and separate storm sewers. These collection systems vary in age from over 100 years old to brand new. Although general design practices in the United States today are not drastically different from 30 years ago, current innovative research in Europe and Japan suggest that broad societal goals such as "sustainability" are not being achieved by current design practices in the United States. Old combined sewers discharge raw sewage to receiving waters. I/I is a costly and wasteful problem associated with sewers. Sanitary sewer overflows (SSO) discharge raw sewage from failed or under-designed separate systems. Stormwater pollution associated with urban areas is discharged from separate storm sewers. Proper transport of solids in sewers is still a misunderstood phenomenon, causing significant operational problems such as clogging, overflows, and surcharging.

This section provides n overview of the problems commonly associated with collection system infrastructure currently in use in the United States. Designers of new collection systems must recognize these problems and address them with modern tools. Unsustainable design practices must not be allowed to be perpetuated in the field of urban water management. The useful life of the infrastructure is too long to simply design big systems to compensate for uncertainty. Following this section are sections describing innovative technologies being investigated and ways they might be used in the 21st century.

Combined Sewer Systems (CSS) CSS now constitute one of the remaining large-scale urban pollution sources in many older parts of major cities (Moffa 1990). In large urban areas, raw sewage, combined with stormwater runoff, regularly discharges to receiving waters during wet weather. Water quality problems arise from the stormwater portion of the discharge mixing with the sanitary wastes associated with the combined sewer. Low dissolved oxygen, high nutrient loads, fecal matter pathogens, objectionable floatable material, toxins, and solids all are found in abundance in combined sewage (Moffa 1990). This mixture has led to some of the more difficult control problems in urban water management. However, CSS problems of today are the result of technology dating back to 1900 and earlier.

Inflow and Infiltration (I/I) Separate sanitary sewers serve a large portion of the sewered area in the United States. These sewers are generally of smaller diameter than combined or storm sewers and serve residential, commercial, and industrial areas. Although sanitary systems are not specifically designed to carry stormwater, per se, stormwater and groundwater do enter these systems. This is a common and complicated problem for sewer owners, so common, in fact, that the design of sanitary sewers must include I/I capacity, which may actually exceed pure sanitary flow rates (ASCE/WPCF 1982). The capacities of many collection systems are being exceeded well before the end of their design life, resulting in bypasses, overflows, surcharging and reduced treatment efficiency (Merril and Butler 1994).

Sanitary Sewer Overflows (SSO) When the capacity of a sanitary sewer is exceeded, untreated sewage may discharge to the environment. SSO may be due to excessive I/I, from an under designed (or overdeveloped) area releasing more sanitary flow than the system was designed for, from a sewer blockage, or from a malfunctioning pump station. The distribution of SSO causes from a sample of six communities is show in Figure 5.1. An SSO can occur at the downstream end of a gravity sewer near the head works of a WWTP or at relief points upstream in the system. I/I is a significant cause of SSO. These relief points may have been designed into the system, or retrofitted to alleviate the problem, or unexpected surcharging through manholes, basements or sewer vents.

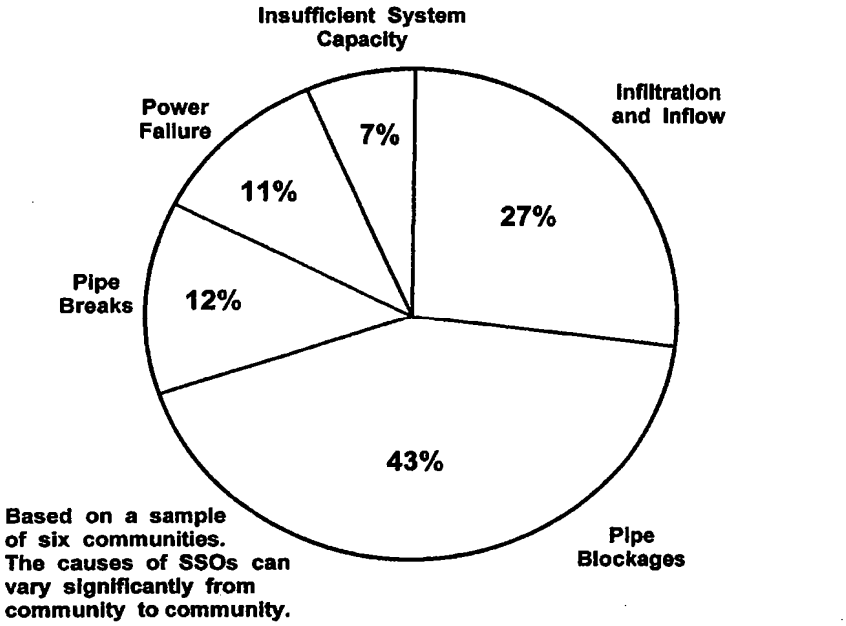

Figure 5.1. Estimated occurrence of SSO by cause (U.S. EPA 1996b)

SSO are undesirable under any circumstance because they result in relatively high concentrations of raw sewage flowing directly to surface waters. Wet-weather SSO may behave in a fashion similar to CSOs in extreme cases, although rehabilitation of the system is different. Instead of treating overflow (as is often the case of CSOs where the CSS provides primary drainage), wet-weather SSO are more typically treated by attempting to remove wet-weather sources , enabling higher flows to the WWTP, or removing hydraulic capacity bottlenecks.

State-of-the-Technology

Combined Sewer Systems (CSS)

The traditional way to control CSO is to first maximize the efficiency of the existing collection system. This may include an aggressive sewer-cleaning policy to maximize conveyance and storage properties of the system, reducing the rate of stormwater inflow, a reevaluation of control points (frequently resulting in raised overflow weirs to maximize in-line storage in a static sense), and alterations of the wastewater treatment plant's operating policy to better accommodate short-term wet-weather flows (WWF) (Gross et al. 1994). These measures were instituted as requirements for CSO discharge permits in 1994 by the EPA. The "Nine Minimum Control (NMC) "Requirements" are (USEPA 1995b):

1. Proper operation and regular maintenance programs for the sewer system and CSO points.
2. Maximum use of the collection system for storage.
3. Review and modification of pretreatment programs to ensure CSO impacts are minimized.
4. Maximization of flow to the WWTP.

5. Prohibition of dry-weather CSO discharges.
6. Control of solids and floatables.
7. Pollution prevention programs that focus on contaminant reduction activities.
8. Public notification to ensure that the public receives adequate notification of CSO occurrences and impacts.
9. Monitoring to effectively characterize CSO impacts and the efficacy of CSO controls.

In creating these permit requirements, the EPA has mandated that all owners must, at a minimum, adhere to these relatively low-cost management activities.

These measures were frequently not enough, and less passive means of controlling CSO have been adopted in many cities. Storage of combined sewage, both in-line and off-line, has been used in a number of locations to capture frequent storms and the "first flush" of large events. As the capacity in the collection system and treatment works increases when the runoff subsides, the stored combined sewage is returned to the system for treatment (Field 1990). Although not completely doing away with CSO (e.g., overflows occur when storage capacity is exceeded), storage of combined sewage has been a cost-effective CSO control method (Walker et al. 1994).

An interesting development regarding CSS is that because of contaminated stormwater runoff from urban areas that require treatment, combined systems are now at least being considered for new urban areas in some parts of Europe. CSS may in fact discharge less pollutant load to receiving water than separate systems where stormwater is discharged untreated and sanitary wastewater is treated fully. In southern Germany, CSS are being designed with state-of-the-art BMPs to reduce the volume of stormwater entering the system. With reduced stormwater input, the number and volume of overflows are reduced over a traditional "old-fashioned" CSS, thus only discharging CSO during large, infrequent events, when the receiving water is most likely to be at high flow conditions also. This concept is discussed in more detail in subsequent sections of this chapter titled, "Innovative Collection System Design - - The State of the Art" and "Future Directions: Collection Systems of the 21st Century."

Separate Stormwater Collection Systems and Diffuse Sources

Separate storm sewers of one form or another can be found in virtually every municipality in the United States. They are typically designed to collect stormwater from urban/suburban areas to prevent nuisance flooding (e.g., usually storms with return frequencies less than 10 years). This "level of protection" from flooding replaces an economic efficiency analysis that would ideally be performed on the basis of the worth of the potential damages resultant from flooding (ASCE/WEF 1993). The selection of return period is related to the exceedance probability of the design storm and not the reliability (or probability of failure) of the drainage system (ASCE/WEF 1993). Typical different levels of protection depending on the land use of the service area are presented in Table 5.1.

Table 5.1. Typical design storm frequencies (ASCE 1993).

Land Use	Design Storm Return Period (years)
Minor Drainage Systems	
Residential	2-5
High value commercial	2-10
Airports (terminals, roads, aprons)	2-10
High value downtown business areas	5-10
Major Drainage System Elements	<100

A more thorough analysis of the expected performance of a drainage system would include a continuous mathematical simulation of the response of the system over an extended period of time using measured rainfall in the service area. This analysis would provide a more accurate estimation of the expected return period at which the capacity of the drainage system would be exceeded and the magnitude of the exceedences. This information may be used in conjunction with property values to estimate the distribution of expected damages that result from system overload, thus providing a more rational basis of design (USACE 1994). In addition, the quality of the discharged stormwater may be mathematically simulated, which would provide information that could be used for receiving water management decisions. A detailed account of the benefits of continuous storm drainage accounting is provided in Heaney and Wright (1997).

Typical elements of a stormwater system include curbs, gutters, catchbasins, subsurface conveyance to receiving water, sometimes first passing through a passive treatment facility such as a dry detention pond, a wet pond, and/or through a constructed wetland (ASCE/WEF 1993). This typical system may have open channels or swales instead of catchbasins and pipes.

Separate storm sewers may transport various forms of diffuse or stormwater pollution to the receiving water. The amount and type of contaminant transported is heavily dependent on the land use of the tributary area, the rainfall/snowmelt characteristics of the area, and the type of storm sewer. Recent studies have shown a relationship between the impervious tributary area and receiving water quality. Although the volume and time to peak of storm hydrographs have long been known to be adversely impacted by imperviousness, the water quality degradation aspects of imperviousness are still not completely understood, and above all, can be mitigated by stormwater management practices.

Solids and Their Effect on Sewer Design and Operation

The fundamentals of modern sewer design have not changed in many respects since the beginning of the century. Review of “Design of Sewers” by Metcalf and Eddy (1914) indicates that the fundamentals of minimum and maximum velocities, grade, flow rate prediction, and solids transport were in place at the turn of the century after hundreds of years of trial and error designs dating back to ancient civilizations. Modern design has significantly refined the

information used in design, but the basic engineering criteria have remained, much to the credit of early sanitary engineers.

The purpose of sewer collection systems has always been to safely transport unwanted water and solids. Historically, sewer design has focused primarily on the volume and flow rate of the fluid and has assumed solids will be carried with the fluid if certain "rules-of-thumb" regarding velocity are followed. This imprecise method of designing for solids transport has been a costly and significant source of maintenance needs over the years in the United States and elsewhere.

Recent research conducted in Europe (Ashley 1996) has focused on the age-old question of transport of solids in sewers. The flow rate, velocity, and size of pipe are all important in determining the amount and size distribution of solids a particular sewer will carry. Therefore, along with flow rate, the solids transport question is one of the most fundamental questions that must be addressed when calculating costs. It is a vexing question, because solids transport is a function of flow rate, velocity, pipe size, pipe material, gradient, solids concentration, size and settling velocity distribution of the solids, and the type of solid (e.g., colloidal or non-colloidal and grit). Also important is the question of solids transformation in the collection system. Fundamental research conducted in Europe has shed some light on this issue (Ashley 1996; Sieker and Verworn 1996; Ackers et al. 1996).

A historic reference to a minimum design velocity is found in Metcalf and Eddy (1914), where an early sewer design in London is cited as using a value of 2.2 ft/s to avoid unwanted deposition in sewers. Other early work on minimum grades for various pipe sizes was done by Col. Julius W. Adams in designing the Brooklyn, NY sewers in 1857 – 1859 (Metcalf and Eddy 1914). Col. Adams' recommended sewer grades are shown in Table 5.2 and compared with modern values found in Gravity Sanitary Sewer Design and Construction (ASCE/WPCF 1982). These early designers recognized that the minimum mean velocity to avoid deposition was dependent on the pipe diameter.

However, in the 1994 WEFTEC proceeding "Collection Systems: Residuals and Biosolids Management," a paper entitled, "Two feet per second ain't even close" by P.L Schafer discusses the problems associated with deposition in large diameter sewers due to using a "rule-of-thumb" design value of 2.0 ft/s (Schafer 1994). Modern design guidelines still state: "Accepted standards dictate that the minimum design velocity should not be less than 0.60 m/sec (2.0 ft/s) or generally greater than 3.5 m/s (10 ft/s) at peak flow." (ASCE/WPCF 1982). One problem with this recommendation is the lack of peak flow definition. Should this be the seasonal, monthly, daily, or hourly peak flow? The frequency and duration of the flushing flow are critical to the proper performance of the sewer. Ideally, a settled sewer particle at the furthest end of the collection system will be reentered into the waste stream and carried to the WWTP. Clearly the minimum velocity design problem has not been resolved.

Table 5.2. Comparison of recommended minimum sewer grades and velocities over the years.

Source	Type of sewer and pipe diameter	Minimum Slope (ft/ft)	Minimum Velocity (ft/s)
Balzalgette, London, c. 1852 (1)	Large intercepting sewers—combined system		2.2
Roe, London, c. 1840 (1)	Large intercepting sewers—combined system	0.002	
New Jersey Board of Health, 1913 (1)	8 in. – Sanitary sewer (n = 0.013) 12 in. – Sanitary sewer (n = 0.013) 24 in. - Sanitary sewer (n = 0.013	0.004 0.0022 0.0008	
Metcalf and Eddy, 1914 (2)	Combined systems Sanitary systems		2.5 2.0
WPCF/WEF, 1982 (3)	Sanitary systems		2.0
WEF/ASCE, 1992 (4)	Storm Sewers		2 – 3
Acker et al. 1996 (5)	150 mm (5.9 in.) 225 mm (8.85 in.) 300 mm (11.8 in.) 450 mm (17.7 in.) 600 mm (23.6 in.) 750 mm (29.5 in.) 1000 mm (39.3 in.) 1800 mm (70.8 in.)	0.0062 0.0043 0.0032 0.0024 0.0021 0.0022 0.0025 0.0028	2.2 2.36 2.46 2.59 2.95 3.48 4.43 6.66

Note:
1. Col. Julius W. Adams (c. 1859) in Metcalf and Eddy (1914)
2. Metcalf and Eddy (1914)
3. ASCE/WPCF (1982)
4. ASCE/WEF (1992)
5. Ackers et al. (1996)

Sewers that exhibit sediment deposition are prone to a multitude of problems over time. Excess sedimentation promotes clogging, backwater, and surcharging and may promote corrosion by producing hydrogen sulfide (Schafer 1994). Because sedimentation problems are more likely to occur in larger diameter sewers, such as trunk sewers, the associated costs of sewer failure may be substantially greater than in a smaller diameter pipe. In combined systems, the storage capacity that is taken up in a heavily sediment-laden trunk or interceptor sewer will tend to increase the volume and frequency of overflow events (Mark et al. 1996). In addition, the deposited sediments in combined systems represent a buildup of pollutants that may resuspend during wet weather (Gent et al. 1996).

When considering sewer collection systems, the proper transport of solids is crucial to a correctly functioning system. There are distinct areas where deposition should be avoided (e.g., the conduit network) and also areas where deposition is desired (e.g., treatment works). The system should function under a wide range of hydraulic conditions and under a wide range of solid loadings. The solids may also vary widely in character, which may alter the performance of the sewer.

To avoid deposition, a common design method is to calculate the shear stress required to move the largest size of particle expected in the sewer under average or high-flow conditions (Schafer 1994). This assumes that the frequency of the high flow is enough to avoid excessive deposition and the subsequent creation of a permanent bed layer. The critical shear stress of a particle is defined as the minimum boundary stress required to initiate motion (Schafer 1994). Chow (1959) indicates that shear stress is a function of the specific weight of water and the hydraulic radius and invert slope of the sewer. Various values of critical shear stress have been recommended, depending on the maximum size of particle found in the sewer. Values of critical shear stress recommended by various researchers are show in Table 5.3.

Table 5.3. Recommended critical shear stress to move sewer deposits (Schafer 1994).

Recommended critical Shear stress		Reference	Conditions
N/m^2	lb/ft^2		
4	0.08	Lynse 1969	Sanitary sewers
4	0.08	Paintal 1972	Sanitary sewers
1.5-2.0	0.03-0.04	Schultz 1960	German systems
1-2	0.02-0.04	Yao 1974	Sanitary sewer with small grit size
3-4	0.06-0.08	Yao 1974	Storm sewers
2.5	0.05	Nalluri 1992	Sand with weak cohesiveness
6-7	0.12-0.14	Nalluri 1992	Sand with high cohesiveness

Note: 1 N/m^2 = 0.02064 lb/ft^2

Schafter (1994) recommends that the lower end of the shear stress range in Table 5.3 is adequate only for waste streams with small particle size and limited grit and when flushing flows may be expected daily. The high end of the range is appropriate when the waste stream contains heavy grit and gravel, as is common in combined or storm sewers (Schafer 1994). Table 5.3 indicates that commonly used design values for the minimum flushing velocities in sewers are not adequate to resuspend grit from large sewers. Consider, for example, a 48- in.-diameter sewer transporting a reasonable load of grit. Minimum velocities in the range of 4.0 ft/s are required to flush deposited grit, far greater than the 2.0 ft/s recommended in some design guidelines. However, European research shows that bed stress is the most important criterion, and a minimum bed shear stress of 2 N/m^2 is required to ensure sediment transport (Ashley and Verbanck, 1997).

Uncertainty in key design parameters is the source of unnecessary cost. If under designed, operation and maintenance costs are likely to be high. If over designed, additional unnecessary capital costs are incurred as are high-maintenance costs due to solids deposition at low flows.

However, in addition to the lack of high-quality frequency/duration information regarding flows, the designer concerned with solids transportation must also contend with a physical process about which only the rudimentary nature is known. The relationship between the solids concentration, the distribution of settling velocities, and the dynamics of movement are not well understood for gravity pipe flow. Operational costs will be incurred if the frequency and

duration of velocities are not enough to regularly cleanse the pipes. Deposition in unclean sanitary sewers will cause SSOs. Thus, environmental costs are also incurred. If over designed, the sewers will remain clean; however, additional excavation and material costs will be incurred.

Although attempts have been made to estimate costs of I/I and SSO on a national basis, there are no cost estimations of improperly designed sewers. It is likely that these costs, if known, would dwarf those for I/I and SSO. As in the case with I/I estimation, new systems that record and store operational data will be invaluable to improving design techniques for solids transport.

Innovative Collection System Design – The State-of-the-Art

Recent work in all aspects of sewer collection systems, from design and facilities-planning level research to construction and operation and maintenance, shows promise for greatly improved collection system performance for the next century. In addition, drastically new technologies that may greatly affect the future configuration of urban water management are being considered. Some innovators in the field are advancing ideas to replace water-intensive waste removal systems.

This section provides an overview of many aspects of sewer concepts. It is generally organized in terms of increasing innovation. In other words, the first examples remain closest to present-day systems, and the last innovations described deviate farthest from current design concepts. The reader is reminded that this section is an overview of innovative ideas in the field of waste management. The section following this one attempts to provide these technologies in a future scenario-type context.

Recent literature in the area of sewer innovation were surveyed from WEF (1994a), WEF (1994b), WEF (1995a), WEF (1995b), WEF (1996), Sieker and Verworn 1996, Ashley 1996, Bally et al. (1996), Henze et al. (1997), USEPA (1991a), and USEPA (1991b). Especially important summary of vacuum, pressure, and small-diameter gravity sewers is presented in USEPA (1991b).

Real-Time Control (RTC) Many fields, including that of urban water management, have barely been able to keep up with the rapid technological and computational advances of the past decade. This has been exacerbated in the United States by the relative longevity of civil infrastructure works and the amount of infrastructure already in place, with most being constructed in the 20th century. As the end of the project life of many of these works is approaching, and as new urban areas are being contemplated for certain high-growth sections of the United States, practitioners and researchers in the field of urban water management have a unique window of opportunity. Now is the time to take advantage of the latest in technological advances and to use the past two decades as a model to predict what the future may bring in terms of technology.

The information age has changed the way in which resources are managed. This fact will be more apparent in new collection systems and waste management of the 21st century. New systems will be operationally data-intensive because of a higher level of control. The current level of control in WWTPs may be seen as extending into the collection system. The increase in data quality and quantity will have positive effects on simulation for design, simulation for

operation, and for real-time control of the system. These innovations should decrease costs and environmental impacts and maximize utility of the system.

Seattle, WA was one of the first major municipal sewer owners in the United States to use real-time measurements of the collection system in a control scheme (Gonwa et al. 1994; Vitasovic et al. 1994). Vitasovic et al. (1994) describes the use of real-time control (RTC) in Seattle for CSO control purposes. Vitasovic (1994) states the goal of the program succinctly:

> …the idea behind RTC of CSO's is fairly straightforward: the conveyance system is controlled in real time with the objective of maximizing the utilization of in-line storage available within the system. The cost of the control system is often a fraction of the cost required for alternatives that include construction of new storage facilities.

The Seattle experience highlights the need for some form of system simulation to test control procedures off-line and to provide a higher level of system knowledge on-line than from data measurement alone (Vitasovic et al. 1994). A supervisory control and data acquisition (SCADA) system provides automation one level above manual process level control and interfaces data retrieval systems with a relational database (Vitasovic et al. 1994; Dent and Davis 1995). Under the SCADA level of control, operators usually manage the system from a centralized location using man-machine interface (MMI) software, receiving data from the SCADA, while maintaining a supervisory level of control over the system (Vitasovic et al. 1994, Dent and Davis 1995). A higher level of automation may be used if a computer controller is used to change system operation. This can include simple control algorithms, such as if-then and set-level points, or may be as advanced as providing on-line nonlinear optimization (e.g., genetic algorithms).

Other successful applications of RTC in the United States include Lima, OH, Milwaukee, WI, and Cleveland, OH. Gonwa et al. (1994) provide a summary of the Milwaukee upgrade of an existing RTC. One new feature of the upgrade was additional control applied to the headworks of the WWTP.

The hydraulic grade line of the Milwaukee system modified by the RTC upstream of the WWTP resulted in 1,500,000 m^3 in-line storage volume during peak storm diversions after interceptor storage is maximized. In other words, the RTC provides control of the system to maximize pipe storage before diverting to the in-line storage system. RTC is used in combination with storage facilities to minimize overflows.

Most applications of RTC, SCADA, automated system optimization and other advanced data management techniques are currently used in collection systems designed before the computer/information age revolution. For new collection system designs, it is imperative that designers understand the physical/structural requirements of long-term high-quality data measurement. Successful design will have adaptivity "built-in." The ability to change operational procedures as technological advances become available will greatly extend the useful life of future collection systems. In other words, future collection systems will have many

critical “high information points” that, used in conjunction with control and simulation, will facilitate operating the system for optimal utilization. The tools used to accomplish this task will change during the project life of the system because of the longevity of infrastructure in contrast with the rapidity of computer technological advances. A successful design will anticipate these changes.

Sanitary Sewer Technology – Vacuum Sewers Hassett (1995) provides a summary of current vacuum sewer technology. A typical vacuum sewer configuration is shown in Figure 5.2.

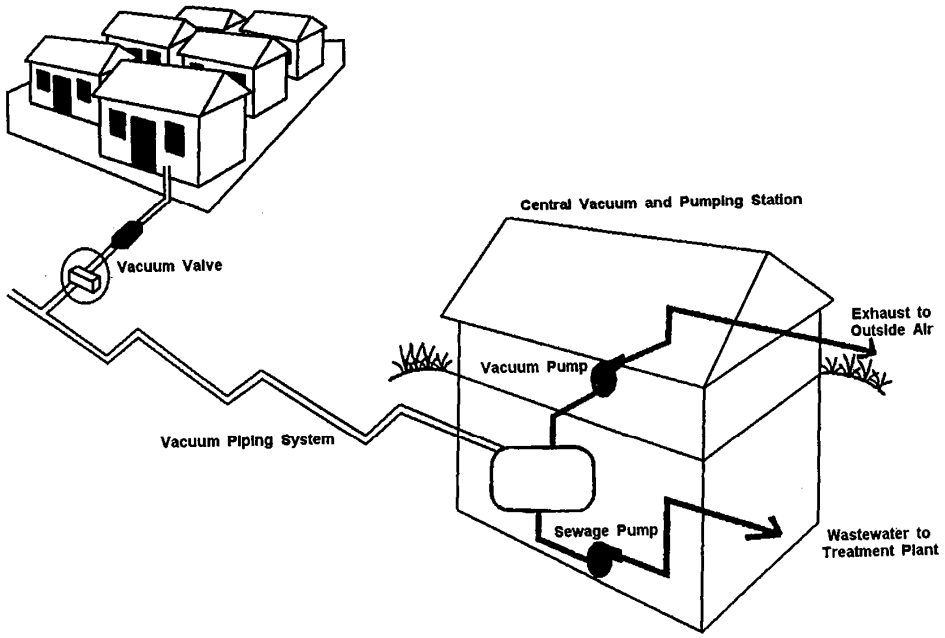

Figure 5.2. Typical vacuum sewer system schematic (Hassett 1995)

Vacuum sewers are typified by shallow pipelines that make them attractive for high-groundwater areas and for alignments that would require expensive rock excavation for gravity lines. Such systems are also useful in flat countries such as the Netherlands. Being completely sealed, vacuum lines also do not have any I/I – a remarkable benefit that begs the question: If vacuum sewer lines can be constructed water tight, why not gravity lines? Vacuum systems do show promise, however, especially with recent advances in lifting capabilities. A recent installation in an Amtrak station in Chicago, IL used a valve configuration that achieved over 20 ft of vacuum lift (Hassett 1995). Another advantage of these systems is the vacuum toilets function with less than a third of water per flush than do modern low-flush toilets, using only 0.3-0.4 gallons per flush, compared to 1.5-6.0 gallons for toilets connected to gravity sewers

Hassett (1995) provides a cost comparison for vacuum sewers for an actual project location in Virginia. The service area was assumed flat with a 3 ft depth to groundwater, an area of 750 acres (300 hectares) and approximately 750 residential units housing 3,000 people. The density

was then varied to provide the construction cost information presented in Figure 5.3 and the operating costs shown in Table 5.4. Hassett (1995) notes that the operating costs of any of the system configurations is only 4-6% of the present value of the capital components and is, therefore, unlikely to be a decision factor. This observation may not be true in countries with higher energy cots.

Table 5.4. Annual operating costs of vacuum and gravity sewer systems as of 1995 (Hassett 1995)

Type of Sanitary Sewer System	Cost (1995 $ U.S.)			
	Labor	Materials	Power	Total
Gravity (Dry)	26,000	3,000	4,000	33,000
Gravity (Wet) [1]	28,000	28,000	4,000	60,000
Modern Vacuum	42,000	10,000	8,000	60,000
High Lift Vacuum	34,000	3,000	8,000	45,000

[1]Wet means that the system includes lift stations and is below the water table.

A major advantage of these systems (along with pressure sewers) is their adaptability to monitoring and control. The use of pressure instead of gravity flow simplifies flow measurement. Control of these systems is more exact than with gravity systems, thereby making them suited for overall system optimization by RTC.

Sanitary Sewer Technology –Low-Pressure Sewers (LPS) Another modern collection system technology that has been used in the United States is the low-pressure sewer used in conjunction with a grinder pump (Farrell and Darrah 1994). These systems use a small grinder pump typically installed at each residence. The grinder pump reduces solids to 0.25 – 0.5 in. maximum dimension (Farrell and Darrah 1994). Like vacuum systems, these low-pressure grinder systems feature watertight piping, thus virtually eliminating I/I. A full system in Washington County, MD went on-line in 1991. Water use, rainfall and wastewater flows were monitored, and wastewater flows were found to be 110-130 gpcd, with no measurable increase during or following wet-weather events (Farrell and Darrah 1994).

A demonstration facility in Albany, NY was installed in 1972, where per capita flows were only 45 gpd. One purpose of this demonstration was to determine the effect of grinding solids on settleability. The conclusion was that there was no effect on settleability and treatability compared with solids transported via a traditional gravity sewer (Farrell and Darrah 1994). Other demonstrations found no significant differences in grease concentrations (Farrell and Darrah 1994). The LPS pipe was excavated after several years of service and significant buildups of solids were noted in the pipes (Farrell and Darrah 1994).

LPS systems have more than a 20-year track record. As with most new technologies, engineers were hesitant to specify these sewers despite smaller capital expenditures due to the lack of long-term experience (Farrell and Darrah 1994). The reliability and costs of operating and maintaining the pumps were a major impediment to widespread use. Reliability of LPS systems has increased dramatically since the first commercial installation at a marina in the Adirondack Mountains in NY (Farrell and Darrah 1994). In the 1972 Albany demonstration project (which

only lasted 13 months), the mean time between service calls for pump maintenance was 0.9 years (Farrell and Darrah 1994). An LPS system installed in 1986 in Bloomingdate, GA averaged 10.4 years between service calls (Farrell and Darrah 1994) over an 8-year period.

As with vacuum systems, LPS systems are well suited for control and monitoring because of the use of pressure rather than gravity to drive the system. This may be significant advantage over gravity systems in the future for RTC applications.

Sanitary Sewer Technology –Small-Diameter Gravity Sewers These systems consist of a system of interceptor tanks, usually located on the property served, a network of small-diameter collector gravity sewers (USEPA 1991b). The interceptor tanks remove settleable solids and grease from the wastewater. Effluent from each tank is discharged to the collector sewer via gravity or by pumping septic tank effluent pumping (USEPA 1991b). A typical system layout is shown in Figure 5.3

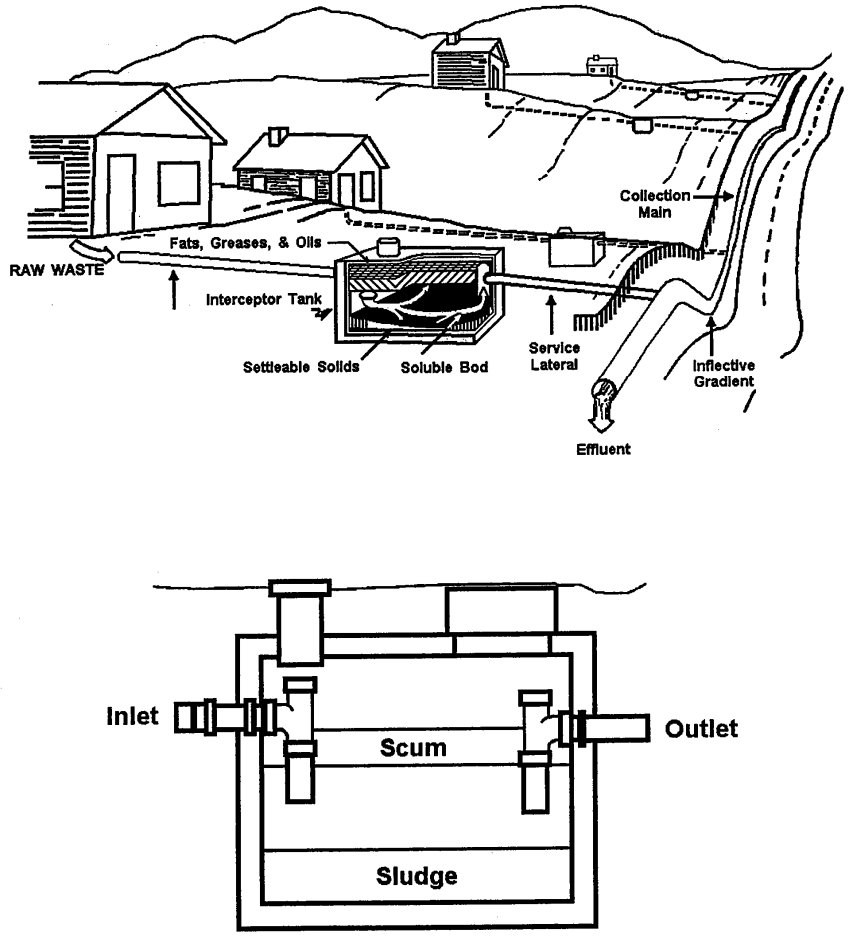

Figure 5.3. Components of small-diameter gravity sewer systems (U.S. EPA 1991b)

This system has the advantage of not having to transport appreciable solids (USEPA 1991b). Cost savings, therefore, result from having a lower required velocity and from less cleaning

costs. Also, peak flows are attenuated in the tank. Therefore, the average to peak flow rate from wastewater is far less than for a standard gravity sewer (USEPA 1991b)

Otherwise, these systems function much the same as traditional gravity sewers. They have been used in rural areas to replace existing septic tank discharge. A problem associated with these sewers are I/I. The use of old septic tanks tend to increase the amount of rainfall induced infiltration (USEPA 1991b)

Blackwater/Graywater Separation Systems

A more drastic break with modern systems is that of water separation at the household level. This has been a relatively active research area in recent years because of its appeal from a water conservation standpoint. Water from faucets, showers, dishwashers and clothes washers drains to a separate on-site filtration device. The filtered water is then typically used for outdoor irrigation. This may be especially advantageous in arid areas where on-site stormwater detention for outdoor use does not meet the evapo-transpiration needs on an average annual basis.

Waste/Source Separation

Recent research in Europe has focused on the separation of household waste in a variety of ways (Henze et al. 1997). The goal of these systems is to promote nutrient recycling and limit entropy gain (a goal for sustainability) via dilution. Urine separation is perhaps the most radical departure, where urine is tanked on-site and converted to fertilizer (Hanaeus et al. 1997). Human urine contains 70% of the phosphorus and 90% of the nitrogen found in wastewater from toilets (Hanaeus et al. 1997). This technology is still in the formulation phase and has only been tested on a limited basis. Research shows it may have applicability for certain waste management applications.

High-Density Areas

Areas with the highest levels of urban stormwater pollution will require stormwater treatment, much as they do today. A form of CSS, or an integrated storm-sanitary system (ISS) (Lemmen et al. 1996) will capture a large portion of the annual runoff volume from dense urban areas. Storm runoff will be reduced by source control and infiltration BMPs/LIDs, and the residual of small events will be transported to the WWTP. Large events will be throttled out of the ISS, before mixing with sanitary waste, and discharged to receiving waters. This new system will have the best of both CSS and separate systems. The advantage of the combined system has been treatment of small runoff-producing events, including snowmelt. However, the disadvantage has always been the discharge of raw sewage to receiving waters during large events. With the advantage of control technology, as the sewers and/or the WWTP reach capacity, the stormwater is diverted directly to receiving waters, without mixing with sanitary and industrial wastes. WWTP will be made larger to afford treating more stormflow.

This system will have a high degree of built-in control. The data stream begins with local radar observations. This information is combined with real-time ground level measurements of rainfall. These data will be used to predict the rainfall patterns over the catchments for the next half hour. The SCADA system receives information about the present state of the sanitary and

storm portions of the waste stream. Quality and quantity are monitored. Performance of high-rate treatment devices operating on the discharged stormwater is monitored. A critical innovation is the integration of the WWTP performance, operation, and control into the system. Operation of the WWTP now extends to the collection system. Rainfall information, in conjunction with the state of the system and receiving water data, are used to predict potential outcomes of the wet-weather event with a system simulation model. Coupled with a non-linear optimization routine, and optimal control scheme is determined on-line, and changes in system control are relayed back to the system via the SCADA system.

The system response is fed back to the SCADA, and continuous control is maintained throughout the wet-weather event. This "feedback" loop provides the municipality with rapid response for flashy summer events and provides urban flood control simultaneously with water quality control. In addition, the time series of wet-weather data are now stored in a relational database, spatially segregated to interface with static geography stored in a GIS.

Future Collection System Scenarios

Innovative Integrated Systems Although old CSS are considered a major source of urban pollution, there is some recent activity in the area of new CSS. Where urban areas have significant amounts of stormwater pollution that requires treatment, it may be possible to design a CSS to capture most of the annual storm volume for treatment at a WWTP, without discharging raw sewage during major events. Lemmen et al. (1996) describe a concept for a sewer system in the Netherlands that has connections between the storm drainage network and the sanitary collection system.

Walesh and Carr (1998) and Loucks and Morgan (1995) describe use of controlled storage of stormwater on and below streets to control surcharging and solve basement flooding in a CSS. The premise of this approach is that stormwater flow rate, not volume, is the principal cause of surcharging of CSS and resulting basement flooding and CSO. On and below street storage of stormwater, strategically placed throughout the CSS, reduces peak stormwater flows to rates that can be accommodated in the CSS without surcharging. The two large-scale, constructed, and cost-effective projects described by Walesh and Carr and by Loucks and Morgan were retrofits. However, the success of these projects suggests integrating the design of streets and CSS in newly developing high intensity areas.

Suburban Development Outlying from the new urban centers, suburban-type development still exists. Although less dense than the city, new suburban development contains some of the mixed land uses found in the urban center. The collection system serving this area is far different from the city, however, because the stormwater pollution is not so severe as to warrant full treatment at the WWTP. BMPs and source control innovations will reduce the stormwater impacts on the receiving water. Regional detention is used for flood control and water quality enhancement while possibly providing recreation**.**

Sanitary wastes are transported via pressure sewers to collector gravity lines at the city's border. The use of pressure sewers has reduced suburban I/I to near zero. In addition, the new sanitary LPS sewers are very easy to monitor, because the age-old problem of open channel flow estimation is avoided by using pressure lines. This provides added certainty in the flow estimation and lends itself very well to control. Technology borrowed from the water distribution field has achieved a great level of system reliability and control. In fact, the sewer now mirrors the water distribution network, essentially providing the inverse service.

Research Questions

1. On a global basis, what is the state-of-the-technology in the field of sewerage system design?

2. Is there a better way to design and operate sewerage systems given the concern for WWF stressors and are there emerging technologies that can be used for treating and controlling WWF at a reasonable cost?

3. What effective watershed management strategies are available and how do communities/utilities select the most appropriate subset from these to match specific watershed needs?

4. How can we effectively prevent and reduce pollutant discharges to receiving waters of the urban watershed?

5. What are the best approaches to retrofit existing and construct new sewer/sewerage systems in urban settings?

Proposed Research

1. Conduct a worldwide search of the literature (including grey literature), WERF, AWWARF, EU, and other international organizations covering advanced sewerage-system design and technology and from that effort, develop a refined research, development and demonstration strategy for NRMRL.

2. Develop and demonstrate innovative integrated sewerage system designs for new urban areas, retrofitting existing urban areas, retrofitting existing CSS, and upstream additions to existing CSS. This project will result in a series of design/guidance manuals for engineers involved with municipal/utility sewerage system upgrading, planning, and design. The initial report will be on innovative integrated sewerage system designs for new and existing urban areas. This report will be the outcome from a comprehensive evaluation and assessment of the current state-of-the-art-technology on innovative approaches for integrating the collection and treatment of dry weather and wet weather flows to achieve optimal water quality protection in the most cost-efficient manner. The initial phase will be to develop a comprehensive inventory of approaches being applied around the world, including approaches for newly developing areas and approaches that consider retrofitting and upstream/upland control techniques for existing systems. Case

studies of the existing applications will be documented. The advanced design strategy shall include but not be limited to:

(1) larger diameter sewers, upland impoundment and flow attenuated via soil infiltration and redirecting runoff, and intermittent mid-stream basins all for the purposes of adding storage capacity and/or reducing flow of/to the system;
(2) steeper sloped sewers with and without more effective bottom cross-sections to reduce/eliminate antecedent dry-weather flow (DWF) pollutant and solids deposition and resulting concentrated storm flushes;
(3) sewer grit/sediment traps and automatic sediment cleaning to reduce and eliminate blockages and high-pollutant load storm-flush events;
(4) upland best management practices (BMP) and low-impact development (LID) to reduce down stream flow and pollutant loads;
(5) sacrificial flood zones to protect down streamed (high-population density/commercial) areas to reduce pollution, drainage channel size, and flood impact;
(6) beneficial use of stormwater for non-potable purposes to reduce water supply demand, pollution/flood impacts;
(7) real-time control to optimize routing and storage capacity to reduce system costs for stormflow control/treatment;
(8) higher WWTP capacity to include treatment of stormflow and not just treatment of peak DWF;
(9) larger interceptors to be in concert with higher WWTP capacity;
(10) higher WWTP hydraulic loading during stormflow events, and
(11) alternative high-rate WWTP treatment methods.

3. Develop and demonstrate methods for stormwater non-potable beneficial use as a means of reducing potable and wastewater infrastructure, municipal water demand, and stormwater pollution, erosion/sedimentation. These stormwater non-potable uses shall include but not be limited to: lawn irrigation, firefighting, greywater, washwater, industrial process and cooling tower, subsurface recharge, and dual-pipe non-potable water supply.

4. Develop and demonstrate planning and design guidance documents on innovative sanitary sewer technologies including vacuum sewers, low-pressure sewers (LPS), and small diameter gravity sewers. The initial report will be the outcome from a comprehensive assessment of the state-of-the-technology of innovative sanitary sewer approaches. The final report will be the result of actual demonstrated technologies.

5. Develop a guidance documents for blackwater/greywater separation systems based on an assessment of the state-of-the-technology and an actual demonstration.

6. Assess and develop a guidance document for waste/source separation technology including the separation of urine on-site and its conversion to fertilizer.

7. Demonstrate an innovative municipal waste management system utilizing advanced sewer designs and waste separation technologies to result in a design guidance report.

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Advanced Concepts – Drinking Water Distribution Systems

Background

Deteriorating water infrastructure, increasing populations, limited water resources, and more stringent water quality requirements pose technical and financial challenges for water utilities. However, these circumstances also provide an impetus for re-assessing traditional drinking water conveyance system designs and practices for the purpose of identifying and selecting more effective and efficient approaches for meeting current and future water quantity, quality, and cost goals.

Another impetus for re-assessing and modifying traditional approaches is the increasing availability of innovative technology that may enable, at a price, more extensive and intensive monitoring, assessment, and control of water quality, hydraulic, and structural aspects of water distribution systems. Examples of innovative technology areas include materials, sensors, communications, computing, modeling, and geographic information systems.

State of the Technology

Advanced concepts for operating distribution systems fall into two broad categories: dual systems and innovation to maintain/improve water quality in traditional distribution systems.

- The dual systems approach involves splitting the distribution system into two systems – one for potable water use only, and the other for firefighting and other non-potable uses. This approach is most amenable to new systems.
- Maintaining/improving water quality in traditional distribution systems does not eliminate the problems posed by combined drinking water and fire fighting systems, but it seeks to minimize them by a combination of design, monitoring, modeling, and control activities.

Dual Systems

Water distribution systems supply water for fire fighting, non-potable uses (e.g., toilet flushing, landscape watering), and potable uses (e.g., drinking, bathing, cooking). Although there are economies of scale from serving all of these needs with one distribution system, there are also adverse effects on drinking water quality, and on the volumes of water that need to be treated to potable water standards. The quantity and pressure requirements for fire fighting dictate much larger pipe diameters and storage tanks than are required to meet potable water uses. "Current practice, together with the need for larger elevated storage tanks for fire protection, results in extremely excessive residence time between treatment facilities and the consumer, which has been shown to be the leading cause of water quality degradation in distribution systems" (Okun, 2005). This causes residence times in current distribution systems to be much longer and more favorable for biological growth and water quality deterioration in the distribution system. Deteriorating water quality requires more aggressive disinfection, which can cause an increase in disinfection byproducts, which have been linked to adverse health effects.

Dual water systems have been introduced to conserve water through beneficial re-use of wastewaters for non-potable uses. "Today in the U.S., some 2000 water utilities, large and small, operate dual systems" (Okun, 2005). However, even in these systems the drinking water distribution system is still designed to meet fire flow requirements, so the long-residence-time issue is not resolved. In fact, if the total flow through the drinking water system declines due to elimination of non-potable usage, then residence time will increase. "A dual system where the possibility of having drinking water distribution systems being relieved of fire protection has only appeared in a few places in the U.S. One is a 1997 paper [Okun, 1997]. Another is a 2002 joint publication of the AWWA Research Foundation, and the Netherland's KIWA; *Impacts of Fire Flow on Distribution Systems*" (AwwaRF and KIWA, 2002). Okun recommends that all future new dual systems be designed and constructed to not only conserve water, but also to substantially improve drinking water quality. He recommends that fire fighting water needs be met with nonpotable water that is distributed separately from drinking water. Separating fire flow from drinking water will enable the water distribution pipes and tanks to be designed, constructed and operated in a manner more conducive to maintaining water quality during distribution. For example, tanks and pipes could be smaller and flow rates higher, which would reduce residence times, biofilm growth, sedimentation, and water quality deterioration. Distribution needs can be met by 2-in. pipes, as opposed to 6-in or 8-in. pipes required to meet fire flow requirements. Also, if stainless steel were used for the distribution pipes, then longer pipe lengths (e.g., 60-ft, compared to 18-ft) and welded joints could be used, which would reduce the number of joints, corrosion, intrusion potential, and leakage. Stainless steel may not require cement liners, which can promote biofilm growth. In a drinking-water-only system there should be substantially reduced costs from pipe installation, treatment, pumping, corrosion control, leakage, and maintenance. The use of much smaller pipes, higher flow rates, less biofilm, corrosion, and less sedimentation would also reduce both the frequency and the volume of water used for flushing. One dual water system that separates drinking water and fire protection has been adopted for a new suburb in Sydney, Australia. The cost savings and water quality improvements for drinking water need to be compared on a case-by-case basis to the technical and economic effects arising from integrating the fire fighting and non-potable water systems.

Innovative Improvement of Water Quality in Traditional Systems

Successful management of a water distribution system requires balancing multiple factors, some of them competitive, in order to meet quantity, quality, pressure, and reliability goals at an acceptable cost. Most existing distribution systems address drinking water, fire fighting, and non-potable uses, so over-sized pipes and tanks, and the potential for excess residence times, excess treatment, and sedimentation are unavoidable facets of the system that have to be addressed in order to maintain or improve water quality. There are also other undesirable water quality conditions, unrelated to fire protection, that have to be managed. Table 1 lists some of the factors and their potential effects on the cited goals.

Table 1. Distribution System Trade-offs

System Feature	Quantity	Quality	Pressure	Reliability	Cost
Fire flow requirements	+	-[1]			
Fire pressure requirements	-[2]		+	-	-[3]
Disinfection		-/+[4]			
Anti-corrosion lining		-/+[5]		+	-
Anti-corrosion additives		+	+	+	-[6]
Measure/model/control flow	+	+	+		-
Measure/model/control water quality		+		+	-
Measure/model/control structural integrity		+		+	-
Satellite/point of entry/point of use treatment		+		-	-
Storage: tanks – size, distance from plant		?		?	?
Storage: in-ground	+	?			+
Active storage mgt.		+			-
Passive storage mgt.		-			+
+ = the system feature has a positive effect on the element in the header					
- = the system feature has an adverse negative effect on the element in the header					
? = direction and magnitude of change is unclear					
1 = water quantity requirements for fire flow dictate larger pipes and therefore longer residence times; longer residence times increase biotic and abiotic reactions, in pipe wall and bulk water, which reduces disinfectant residual, allowing re-growth of pathogens					
2 = high pressure increases leakage					
3 = increased leakage wastes the investment in treatment and pumping the lost water					
4 = disinfection of pathogens is a positive; disinfection byproducts a negative					
5 = linings can promote biofilm growth; linings reduce corrosion/tuberculation					
6 = Zn-containing additives reduce corrosion, but may affect disposal cost of wastewater treatment residuals					

Innovative technologies and procedures can potentially help determine and maintain the desired range of system performance. Relevant technologies include:

- pressure, flow, water quality, corrosion, and structural integrity monitoring that is more intensive, extensive, rapid, accurate, and economical
- predictive models for pipe and tank hydraulics and water quality
- predictive models for contaminant formation, depletion, and migration
- predictive models for structural deterioration and failure
- cost models

- communications and control systems integrated to measurement and modeling systems that enable necessary and timely decisions and adjustments of flow rates, flow paths, pressure, disinfectant, corrosion control, and inspection and maintenance activities
- storage tank design or operation modifications to reduce residence time
- point of entry or point of use treatment

Technologies in the above categories already exist, but further improvement, evaluation, or verification is needed to support user community decisions on their use. For example, the development and integration of distribution system computer models, graphical user interfaces, and geographic information systems has greatly improved and simplified the process of distribution system modeling. "Modeling water distribution systems with computers is a proved, effective, and reliable technology for simulating and analyzing system behavior under a wide range of hydraulic conditions." (Ysusi, 1999). There are a wide range of distribution system models available. However, further improvements are needed for hydraulic models for: multiple sources of supply with variable water quality, pipe wall/water column interactions, disinfection byproducts (DBP) kinetics over time and space, transient low pressures, intrusion flow and quality, dead end spatial and temporal demands, and cost modeling.

This research will be closely coordinated with other research organizations that have completed, ongoing, or planned projects on topics in this area.

Research Questions

1. How can distribution systems be designed, constructed, and operated to achieve a better balance between water quantity and quality requirements, fire protection, and cost?
2. How can measuring, sensing, modeling, and system control be improved and effectively integrated to improve water quality and system efficiency?

Proposed Research

1. **Dual Systems**
    a. **<u>Retrospective</u> Assessments of Dual Systems for Potable and Non-potable Uses –** This project will document the efficiency and performance of in-service dual systems. Factors considered will include reliability, energy, water quality, efficiency, water conservation, performance, cost, and applicability.
    b. **<u>Prospective</u> Assessments of Dual Systems for Potable and Non-potable Uses** – Criteria will be developed for determining potential applicability, benefits (including water quality improvements) and costs of dual systems (with a potable-water-only component) for new systems. Consider reliability, energy, water quality, efficiency, water conservation, performance, and cost, etc. In cooperation with others (e.g., Watereuse Association), candidate, representative systems will be identified and evaluated against the criteria. If the results are positive, promote the use of this type of system where applicable, especially those receiving substantial federal funding. This project will also be conducted in close collaboration with the Water Science and Technology Board of the National Research Council, which recently completed a report on health impacts of

distribution systems. Pending results of the first project, follow up products may include the following:

i. A guide for estimating benefits-costs of dual systems
ii. A national estimate of the benefits and costs of installing dual systems
iii. An assessment of benefits and costs of installing dual systems in Border 2012 projects. Border 2012 is a US-Mexico border area environmental program). http://epa.gov/border2012/pdf/2012_english.pdf
iv. An assessment of the benefits and costs of dual systems for addressing persistent water quality problems.

2. **Evaluate/Improve distribution system models –** Evaluate and improve hydraulic models' ability to handle: multiple sources of supply with variable water quality; pipe wall/water column interactions; DBP kinetics over time and space; transient low pressures; intrusion flow and quality; dead end spatial and temporal demands; and, cost modeling. This project will also evaluate performance, cost, and benefits of innovative options for incorporating real-time data collection into daily treatment plant operation and distribution system operation (e.g., change flow routes, change tank operation) to improve water quality in the distribution system.

3. **Evaluate/Improve innovative distribution system designs –** This project will evaluate benefits and cost of non-dual system design options that can improve drinking water quality. Candidate improvements include: improved network design; storage volume (in-ground, tanks); tank location/operation (e.g., near treatment plant; strategically placed throughout system; a few large tanks vs. many smaller tanks; in/out configuration; drawdown strategy); real-time monitoring (e.g., multiple strategic monitoring locations; advanced management of water quality, flow, and integrity; interfacing distribution system operation with the treatment plant). The research program will primarily address distribution , but some treatment options may be addressed in later years of the research program, such as: decentralized/on-site hybrid systems; advanced treatment strategically placed; and in-distribution-system treatment (e.g., package plants, POU, POE).

4. **Pressure management for new systems -** Pressure management is one of the most effective new approaches to leakage control. It may provide the added advantage of reducing main breaks. This project will identify and evaluate new infrastructure options with adequate controls (e.g., district metering, pressure controls) for monitoring and maintaining efficiency. Potential water quality, energy, cost, and other effects will be evaluated. The basis for fire flow/pressure requirements for drinking water systems will be assessed to determine whether pressure can reduced, since many methods and local ordinances and building codes that may be overly conservative can drive pressure requirements. An assessment will be made as to whether significant changes are justified and how they would affect water quality, quantity, and cost.

5. **Adaptive water and wastewater engineering analysis and guidelines for sustainable development** – This project will develop and evaluate engineering and management adaptation methods and techniques for sustainable water and wastewater infrastructure operations under the new global change environments. Project focus will be storm

water/wastewater collection and conveyance design and operations, water treatment, and distribution on a region-by-region basis and in watershed scales.

6. **Optimized water distribution systems** – The objective of this research is to develop a generally agreed to, practical, reasonably achievable, definition of "optimized" water distribution system. This effort will require bringing diverse perspectives into common perspective and desired level of service considerations and cost considerations. This topic was supported at the workshop, but due to other ongoing activities by AwwaRF, Pennsylvania DEP, and US EPA, it will be re-visited later in the program to determine whether additional basic or applications research is necessary. The ongoing research will be monitored for collaboration or follow-up opportunities. The relevant ongoing research is AwwaRF's RFP 4109 (Criteria for Optimized Distribution Systems), which has as its objective to "define and develop a continuous improvement program based on optimization principles for water distribution system operation. In particular a self-assessment approach needs to be developed that defines critical components and objectives of optimized distribution system operations, and then also defines metrics measuring the degree of optimization…." AwwaRF RFP 4109 builds on previous projects/reports, including Development of Water Quality Optimization Plans (2005). Since 2005, US EPA's Technical Support Center (TSC) of the Office of Ground Water and Drinking Water has been working on the development of a distribution system (DS) optimization program, and the Pennsylvania Department of Environmental Protection (PADEP) began an initiative to develop a distribution system optimization program in 2006. Also, as part of the Center for Distribution Systems Optimization, the University of Cincinnati is conducting research on distribution system optimization, with a particular emphasis on factors affecting disinfection byproduct formation.

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Innovative Treatment Technologies for Wastewater and Water Reuse

Background

With the passage of the Clean Water Act in 1972, the National Pollutant Discharge Elimination System (NPDES) Program was established to control the release of deleterious pollutants from discrete point sources into our nation's waterways. As it applies to municipal wastewater treatment plants, also referred to as Publicly Owned Treatment Works (POTWs), the NPDES program establishes both technology-based and water quality based treatment requirements to be achieved. Technology-based requirements for POTWs have been established in the "secondary treatment standards" which reflect the proper performance of typical biological treatment plants. These standards establish POTW performance levels for the discharge of 5-day biochemical oxygen demand (BOD5) and total suspended solids (TSS) of 30 mg/l. In some cases, secondary treatment standards are not sufficient to support the attainment of state water quality standards in the receiving water. In these situations, water quality-based treatment requirements must be established for a POTW. These more stringent treatment requirements may result in tighter controls on BOD5 and TSS. In many cases, water quality-based treatment requirements for POTWs address additional pollutants, including nutrients (nitrogen and phosphorus) and metals. The majority of POTWs in the U.S. were constructed during the 1970s and 1980s, when the Federal Construction Grant Program was subsidizing a major proportion of the construction costs. As these treatment plants begin to reach the end of their design lives and as their effluent quality requirements are becoming more restrictive, the need to rehabilitate or upgrade treatment will expand and innovative treatment technologies will be in demand.

In addition to addressing aging wastewater treatment challenges, the demand for more cost-effective municipal wastewater treatment technologies is being driven by many other factors. There is a growing challenge to more effectively manage and treat peak wet weather flows at wastewater treatment plants, especially focusing on the effectiveness of pathogen reduction. New and emerging contaminants, such as endocrine disrupting compounds (EDCs), pharmaceuticals and personal care products, present challenges not only relating to their fate through a wastewater treatment plant and into the environment, but to their potential capacity to interfere and inhibit treatment effectiveness. The control of nitrogen and phosphorus is a growing priority, especially in the basins that drain to the Mississippi River, Great Lakes and the Chesapeake Bay. There is an ever present demand for wastewater treatment technologies that are more energy efficient and produce smaller volumes of residuals.

The demands for water around the nation are driving an increasing demand for alternative sources, especially for non-potable wastewater and stormwater reuse. Depending on the nature of the wastewater and stormwater source and the intended reuse application, treatment requirements may exceed tertiary levels and demand the use of advanced filtration and membrane technologies.

Unlike the NPDES program which regulates point source discharges on a national basis, the regulation of wastewater and stormwater reuse in the U.S. is controlled at the state level. In late-2002, 25 states had adopted regulations on the use of reclaimed wastewater, 16 states had guidelines or design standards, and 9 states had no regulations or guidelines. (EPA, 2004) While

there are no national regulations that apply to water reuse in the U.S., the EPA, along with the U.S. Agency for International Development (USAID), published the "2004 Guidelines for Water Reuse (EPA/625/R-04/108)." These guidelines were published to help utilities and regulatory agencies determine appropriate levels of treatment for reclaimed municipal wastewater.

State of the Technology

For municipal wastewater treatment, biological treatment processes are the most predominantly applied technologies. Biological treatment utilizes microorganism populations to degrade organics and nutrients in the wastewater. As microorganisms consume these compounds, they are converted to biomass and removed by subsequent processes. Biomass can be either fixed or suspended and treatment processes can be either aerobic or anaerobic. In addition to these conventional biological treatment processes, currently practiced municipal wastewater treatment includes physical and chemical treatment processes. Course screening and preliminary settling processes typically precede biological treatment. In addition, secondary settling is applied to remove excess biomass from biological systems. Finally, after secondary clarification, a disinfection step is utilized to address potential pathogens in the treatment plant effluent. Typically, chlorine is added to the wastewater and adequate contact times provided to promote pathogen kills.

There have been many recent advances in biological treatment technologies. In addition to becoming more cost-effective, especially in terms of energy consumption, many of these emerging and innovative technologies can be easily retrofitted into aging systems, can result in treatment systems with smaller "footprints," and can enhance treatment effectiveness, especially for nutrient removal.(EPA, 2007) Innovative biological treatment technologies emerging over the past several years include:

- Membrane bioreactors (MBR),
- Mobile bed biofilm reactor technology (MBRT),
- Integrated fixed-film reactor technology (IFAS), and
- Biological aerated filters (BAF).

Recent innovative technology development in the area of physical chemical treatment processes include membrane filtration, compressible media filters, cloth media filters, fine grit removal and disinfection processes.(EPA 2007) Some of these technologies include:

- Fine/Advanced grit removal system (AGRS),
- Microfiltration/Microseive,
- Ultrafiltration,
- Nanofiltration, and
- Ultraviolet disinfection.

Treatment technologies for reclaimed wastewater reuse are mostly developed from the physical, chemical and biological treatment processes applied to municipal wastewater and drinking water. Most existing regulatory standards for wastewater reuse can be met by applying conventional treatment practices. However, the treatment effectiveness of these conventional technologies on

new and emerging contaminants, such as endocrine disruption compounds (EDCs), pharmaceuticals and personal care products is uncertain due to limited data and information. As the demand for high-quality reclaimed wastewater increases, the application of new and innovative technologies, such as MBRs, microfiltration, ultrafiltration, nanofiltration, and reverse osmosis will also increase.(Levine and Asano, 2004)

Research Questions

The following key research questions relating to emerging and innovative treatment technologies for municipal wastewater and water reuse have emerged from input and comments from key internal and external stakeholders and recent work completed by EPA's Office of Wastewater Management on innovative and embryonic treatment technologies.(EPA, 2007) These key research questions reflect critical gaps in our knowledge of the performance of new and innovative treatment technologies, especially when determining technology performance for the review and approval of permits and determining the suitability of specific technologies to address site-specific treatment challenges.

- Can emerging and innovative treatment technologies, for both municipal wastewater and water reuse, be identified, evaluated, verified and demonstrated in field settings to improve our understanding of their applicability, cost-effectiveness, technical performance, and reliability?

- Can knowledge of the performance and reliability of municipal wastewater treatment technologies and systems be transferred to the application of these technologies or the development of new technologies in meeting the water quality requirements for water reuse?

- Can new and innovative treatment technologies and systems be evaluated based on the performance of full-scale installations to better inform utilities and regulators and provide reliable, objective technical assessments?

- Can established treatment technology and system design, operation and maintenance practices be updated based on information on the performance, cost-effectiveness, and reliability of new and innovative technologies?

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 proposed. Each proposal indicates the estimate time frame for the work. While these proposals address the issues in the questions above, modified, alternative or additional projects may evolve as this plan is implemented.

1. **Technology Transfer Product: Nitrogen Control Design Manual** – An updated technology design manual based on the original EPA manual published in 1975 and updated in 1993 (EPA 625/R-93/010). This manual will reflect innovations in controlling nitrogen discharges from municipal wastewater treatment plant and present up-to-date design procedures. This design manual will reflect recent technology assessments completed by EPA's Office of Wastewater Management. (12-18 months)

2. **Technology Transfer Product**: **Phosphorus Removal Design Manual** – An updated technology design manual based on the original EPA manual published in 1971 and updated in 1975 and 1987. This manual will reflect innovations in the removal of phosphorus from municipal wastewater treatment plant discharges and present up-to-date design procedures. This design manual will reflect recent technology assessments completed by EPA's Office of Wastewater Management. (12-18 months)

3. **Technology Transfer Products**: **Technology Design Manuals and Handbooks** – Based on the information and data generated from the treatment research, demonstrations, evaluations, verifications, and assessments conducted under this plan, it is expected that several technology design manuals and handbooks will be developed. These manuals and handbooks will provide up-to-date technical guidance on the application of municipal wastewater treatment technologies and treatment technologies for water reuse. (24-60 months)

4. **Applied Technology Research, Evaluation and Demonstration: Water Reuse Applications of Wastewater Treatment Technologies** – This project will be a multi-year effort that will include pilot-scale research of treatment technology effectiveness on conventional and emerging pollutants; pilot-scale fate and transport studies in simulated water reuse applications; development of monitoring indicators and analytical techniques; and predictive models for engineering design and evaluations. (48-60 months)

5. **Wastewater Treatment Technology Evaluations** – These evaluations will address knowledge gaps on the performance, cost-effectiveness and reliability of new, innovative technologies emerging into practice. These evaluations will use full-scale installations of technologies to provide reliable, objective data and information for use in technology selection by utilities and in permitting programs by state and EPA regional staff. It is likely that one of the initial technology evaluation projects will be on membrane bioreactors. (24-60 months)

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