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Decision-Support Tools for Predicting the Performance of Water Distribution and Wastewater Collection Systems

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Notice

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Foreword

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory is the Agency's center for investigation of technological and management approaches for reducing risks from threats to human health and the environment. The focus of the Laboratory's research program is on methods for the prevention and control of pollution to air, land, water and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites and ground water; and prevention and control of indoor air pollution. The goal of this research effort is to catalyze development and implementation of innovative, cost-effective environmental technologies; develop scientific and engineering information needed by EPA to support regulatory and policy decisions; and provide technical support and information transfer to ensure effective implementation of environmental regulations and strategies.

This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

Hugh W. McKinnon, M.D., Acting Director
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Abstract

Water and wastewater infrastructure systems represent a major capital investment; utilities must ensure they are getting the highest yield possible on their investment, both in terms of dollars and water quality. Accurate information related to equipment, pipe characteristics, location, site conditions, age, hydraulic rates, and water quality is critical to industry and municipalities to enable the most cost-efficient operation, maintenance, and rehabilitation of existing systems. This report summarizes information on European efforts to optimize operation, maintenance, and rehabilitation activities related to water distribution and wastewater collection systems. The report includes a description of:

- the capabilities and the data required to run eight pipe assessment software applications or models,
- the infrastructure performance indicators used by three European water authorities, and
- an approach to collect the necessary performance indicator (PI) data, based on our assessment of the European experience.

Based on the review and analysis of European research and product literature related to the use of models for rehabilitation management, there does not appear to be a widespread use of modeling applications in Europe. Each model presented in this report has been applied in selected urban or rural water services but not on a large national scale. UtilNets is the most comprehensive model. It contains capabilities to model pipe failures, water quality, and rehabilitation scenarios. However, it is only in the prototype development stage. The concept of modeling the impact of pipe failures on water quality and using that information for rehabilitation planning has not yet been implemented in practice. Only the EPAREL/EPANET and UtilNets models have integrated a water quality module.

Data collection costs associated with using models are high; accordingly, water services must avoid the collection of unnecessary data. The minimum data elements required by the models to develop a prioritized list of pipes based on risk of failure include: pipe material, pipe age, section length, number of breaks or bursts, and diameter. Additional information such as location, date and nature of last break, type and cost of rehabilitation options, and type of customers that would be affected by a service interruption, is necessary if managers are to assess the impact of different rehabilitation scenarios.

Spatial analysis plays an important role in rehabilitation planning since the research shows that a significant number of failures appear in geographic clusters. However, only four of the models (i.e., AssetMap, Gemini VA, KureCad and UtilNets) integrated a geographic information system (GIS) user interface.

Based on a review of three case studies and European research papers related to the use of performance indicators, it was found that the practice of using performance indicators as a management tool is not widespread or standardized across European countries. Only the UK is using a well-defined and nationally standardized approach. However, even in the UK, there has been no study of the costs of additional data collection versus the benefits of additional system serviceability. The PIs used in the case studies varied considerably, but could be grouped into indicators of: network type and size; customer service; water distribution system effectiveness and reliability; wastewater collection system effectiveness and reliability; environmental impact; and infrastructure construction and rehabilitation cost-effectiveness. The performance measurement system in the UK was found to be the most developed and could serve as a model for the US. Although all of the case studies provided examples of how PIs could be used for intra-system and inter-system comparisons, only the UK's OFWAT uses PIs to approve rehabilitation plans and price rate changes. A private water authority must demonstrate via PIs how its rehabilitation plans will improve the distribution or collection systems' serviceability to customers.

Based on the finding of this study, it is recommended that a web-based survey of industry, state and local government officials, and academic and professional groups be developed. The purpose of the survey would be to select the most important performance indicators, create uniform definitions, and verify the core data elements necessary to support the selected indicators. The results from the web survey could serve as a basis to convene an expert steering committee to provide direction to the development, fielding and use of the database. Participation should include representatives of industry, local government and water authorities. Once uniform definitions are developed, volunteer water authorities should be solicited to collect the data necessary to develop a statistically significant database of infrastructure performance indicators.

Acknowledgments

For its review of operation and maintenance practices related to the use of decision-support tools, the LMI study team obtained information from the European Cooperation in the field of Scientific and Technical Research (COST) C3 group that addresses the diagnosis of urban infrastructure. In addition, the research was based on review of current European technical literature, case studies, and interviews with European and United States practitioners. The LMI study team consisted of Mr. Steve Stone, P.E., Mr. Emil J. Dzuray, Ms. Deborah Meisegeier, Ms. AnnaSara Dahlborg, and Ms. Manuela Erickson. We would like to acknowledge and express appreciation to Dr. Peter Stahre, Dr. Sveinung Saegrov, Dr. Paul Conroy, Dr. Gerald Jones, Prof. Dr.-Ing. Raimund Herz, and Mr. Keith Edwards who helped refine the scope of this study, provided research materials and provided an overview of key issues in the European infrastructure management community. In addition to these European experts, we would like to express our appreciation to Mr. Michael R. Caprara, Project Manager, American Water Works Association Research Foundation for his assistance in identifying appropriate research documentation.

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Abbreviations

ABS	acrylonitrile-butadiene-styrene
AWWARF	American Water Works Association Research Foundation
COST	Cooperation in the field of Scientific and Technical (Research)
CPVC	chlorinated PVC
DWI	Drinking Water Inspectorate
EA	Environment Agency
USEPA	U.S. Environmental Protection Agency
ESW	East Scotland Water
EU	European Union
GIS	geographic information system
IRR	incident ratio rate
MOU	memorandum of understanding
O&M	operations and maintenance
OFWAT	Directorate General of Water Service
OM&R	operations, maintenance, and rehabilitation
PB	polybutylene
PE	polyethylene
PI	performance indicator
PVC	polyvinyl chloride
R&D	research and development
SDWA	Safe Drinking Water Act
VAV	Swedish Association of Water and Sewage Works

Chapter 1
Introduction

Background

The United States' water and wastewater infrastructure systems represent a major capital investment. Accordingly, utilities strive to get the highest return possible on that investment, both in terms of dollars and water quality. Of the approximately 200,000 public water systems in the US, about 30% are community water systems that serve primarily residential areas and 90% of the population. Potable water conveyance within these 60,000 community systems represents an estimated 850,000 miles of pipe. Much of this pipe has been installed since World War II. Approximately 26% of that pipe is unlined cast iron and steel that has been judged to be in fair or poor condition. From a structural and hydraulic viewpoint, that pipe will require accelerated repair and replacement. Similarly, wastewater collection systems are an extensive part of the nation's infrastructure. In the US, approximately 147 million people are served by about 19,000 municipal wastewater collection systems representing some 500,000 miles of sewer pipe.

As these urban infrastructure systems age, more preventive maintenance, repair and replacement of existing systems will be required. The Congressional Budget Office estimated that the total public spending on wastewater infrastructure was approximately $22 billion in 1994 alone. This represented 13% of total infrastructure spending in the US. The cost of building, operating and maintaining water and wastewater facilities over the next 20 years is projected to be $95 billion per year.[1] In order for municipalities to cost-effectively plan, organize, and implement this maintenance and renewal effort, they will need more extensive information about pipe system structural conditions, enhanced decision-making tools, improved operation and maintenance practices, and state of the art techniques for repair and rehabilitation. Exemplary European water distribution and wastewater collection systems are potential sources of novel and efficient infrastructure maintenance and rehabilitation practice improvements, which should be considered by US researchers and utilities.

Despite the high cost and the key role that wastewater collection systems play in servicing the public and protecting the environment, a study by the National Research Council[2] found that few or no standards exist for evaluating its performance. Pipe age is clearly a factor; however, it is usually a combination of several factors that causes failures and influences maintenance decisions. This complicates the decision-making process. To effectively manage maintenance and rehabilitation programs, managers are looking more and more for a quantitative picture of the condition and

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[1] Water Infrastructure Network, *Clean and Safe Water for the 21ST Century: A Renewed National Commitment to Water and Wastewater Infrastructure*, The Water Infrastructure Network, Washington, D.C., 2000. From the RAC website http://www.rebuildamerica.org

[2] National Research Council Committee on Measuring and Improving Infrastructure Performance, Measuring and Improving Infrastructure Performance, National Academy Press, Washington D.C., 1995.

performance of their systems. Conceptually, this quantitative picture can be generated through the selection of a suitable set of performance indicators, followed by collection of the required data and analysis of the information using computer applications.

Objective

The overall objective of this project was to identify and describe European practices that managers are using to make rehabilitation decisions (performance indicators) and the non-hydraulic models for predicting failures, and managing and optimizing the operation and maintenance of water distribution and wastewater collection systems. This report also recommends a conceptual framework for developing a standardized US national database that could maintain performance indicators related to pipe failures, their causes, repair costs, and other important factors.

Approach

The LMI study team worked with USEPA staff and European experts to develop a study outline and identify reference materials. Appendix A provides references and Appendix B a list of experts contacted for this study. The research was based on a review of current technical literature (English and select European languages), case studies, and interviews with European practitioners and researchers. A four-step approach was used in assessing decision-support tools:

1. Identify existing non-hydraulic models.
2. Categorize and describe pipe assessment methodologies and software applications that assist managers in quantifying and ranking the condition of pipelines.
3. Based on the methodologies and software applications identified, develop a list of recommended data elements to be collected for use in decision making.
4. Identify existing management approaches to collect, evaluate and utilize performance indicator data for decision making.

To determine essential information for rehabilitation planning, the decision-making process for both water and wastewater pipelines was examined.

Overview of the Rehabilitation Planning Process for Water and Wastewater Pipes

A rational decision to replace or to not replace a pipe at a particular time is often made by evaluating two alternatives:[3]

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[3] Shamir, U., and C. Howard, "An Analytic Approach to Scheduling Pipe Replacement." Journal of The American Water Works Association (AWWA), pp. 248-258. New York, NY: The AWWA, May, 1979.

- replace a pipe, incurring the replacement cost and future costs associated with the new line, or

- retain the existing length of pipe, saving the replacement costs, but incurring increasing costs of repair, disruption of services, and damages.

The process infrastructure managers use to make this rehabilitation decision can be categorized as either proactive or reactive.

Reactive rehabilitation approaches are quite simple in that a manager repairs a pipe only after it fails to meet its performance requirements such as hydraulic carrying capacity (i.e., experiences a break, blockage, low pressure, excessive overflows, or excessive leakage) and water quality (e.g., excessive rust in distributed water). The benefit to this approach is that a pipe section realizes its full economic life. The disadvantage of this approach is that the cost of fixing a pipe after it fails is unplanned and may be more than fixing it prior to failure. In addition to the potential for increased and unplanned direct rehabilitation costs, there may be additional indirect costs due to customer service interruptions, damages to co-located utilities, damages to property, and traffic interruptions.

In a proactive rehabilitation approach, a manager attempts to rehabilitate a pipe section prior to its failure. Although there are many variations to proactive rehabilitation management, the approaches typically involve the following steps:

- Step 1. Identify performance indicators for the entire network and each pipe section. These performance indicators may include hydraulic capacity (i.e., flow rate, pressure, and leakage rates), water quality (i.e., compliance with regulatory standards, bacterial growth, taste, color, and odor), customer service (i.e., number of interruptions), cost-effectiveness, and environmental impact (i.e., number of combined sewage overflows).

- Step 2. Assess the network's characteristics (i.e., pipe lengths, size, material, age, operational conditions, and environmental conditions), functional capabilities (i.e., hydraulic capacity and water quality) and structural condition. This step usually culminates with managers assigning each pipe section[4] a condition classification.

- Step 3. Prioritize the pipes for rehabilitation. Since the proactive approach requires managers to replace pipes before they fail, managers must estimate the future date on or about which a pipe will fail. Typically managers use the projection of when the pipe will break as the primary basis for prioritization, but can also consider a wide variety of other decision attributes such as economics, risk of customer service interruptions, risk of property damage, risk of utility damage, water quality impacts and environmental impacts. The prioritization

[4] In practice, managers have classified pipe sections using different approaches to include by each discrete section of pipe (e.g. each 10' length) and by similar pipe characteristics (e.g. all cast iron pipes greater than 50 years old).

process can also involve predicting future benefits and implications of different rehabilitation strategies.

- Step 4. Select potential options for corrective action or rehabilitation. In this step, managers attempt to select the most cost-effective rehabilitation option. Since this step requires comparing corrective actions that have different initial costs, operating costs and life expectancy, managers often use economic models to support the selection process.

- Step 5. Implement rehabilitation options and reassess system performance. In this step, managers implement the rehabilitation options and determine the overall effectiveness of the selected rehabilitation strategy by assessing the network's performance over time and by comparing its performance to other systems.

Since the goal of proactive infrastructure management is to minimize life-cycle rehabilitation costs for an infrastructure network while meeting its performance targets, thorough economic analysis is essential. The desired degree of economic analysis requires the following information:

- projected number of failures in future years in the existing pipe,
- projected number of failures in the new or rehabilitated pipe from the time it is installed,
- cost of repairing one break or failure,
- cost of replacing the existing pipe with a new one, and
- discount rate used in converting future expenditures to present value.

If this information is known, managers can calculate the following parameters as illustrated in Figure 1-1:

- The present value (dollars) of all future repair costs for the existing pipe shown as a function of the replacement year.
- The present value (dollars) of replacing the existing pipe with a new pipe shown as a function of the replacement year.
- The total life-cycle cost shown as a function of replacement year, which is the sum of the present value of all future repairs and the present value of replacing the pipe.
- The optimal year for replacement which is equal to the year at which total life-cycle cost is minimum.

The costs shown are expressed as current dollars (present value) to facilitate the comparison of alternatives. Future expenses are discounted using a rate based on both inflation and the interest rate normally involved in the utility's financing. It is important to note that studies[5] have shown

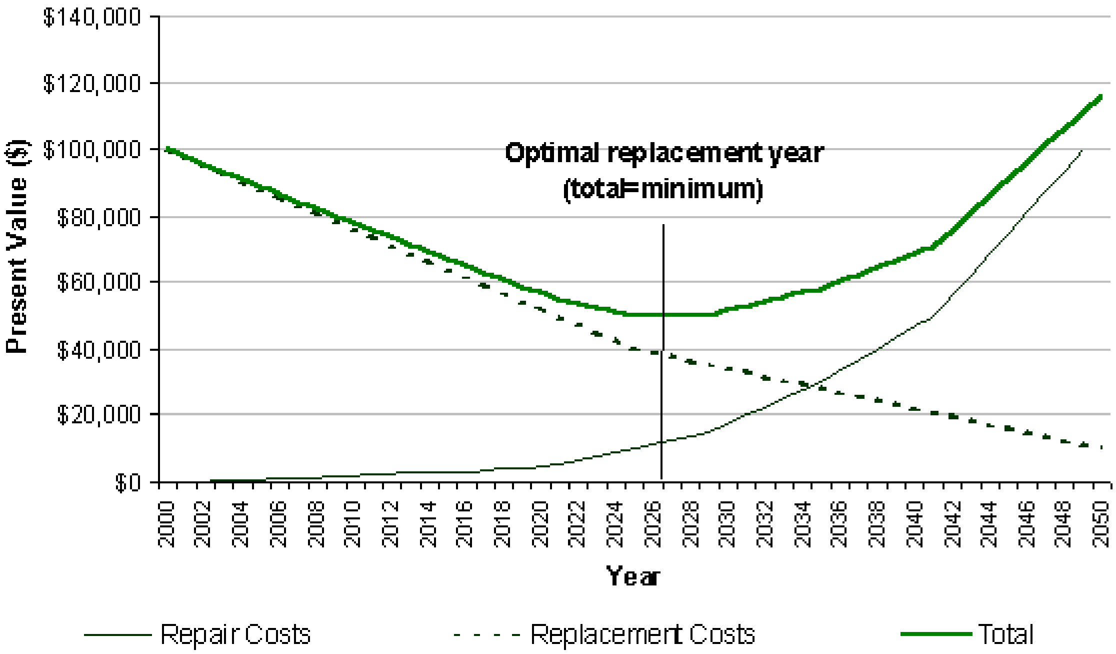

Figure 1-1. Sample forecast of repair and replacement costs (present value) to determine optimal pipe replacement year.

that this type of economic analysis is very sensitive to model parameters (forecasted break rates, discount rates, and costs) that are difficult to accurately determine.

The forecast of pipe break rates can be derived from an analysis of previous failure data collected from maintenance records using stochastic analysis, such as Poisson or Weibull models. This analysis can also be based on a correlation between various network attributes (age, length, season, pipe material, diameter, soil type, traffic conditions, loading, or location) and failure rate. The result of such analysis is an estimate of failure rates for either groups of like pipes or for each pipe section

5 Shamir, U., and C. Howard, "An Analytic Approach to Scheduling Pipe Replacement." Journal of The American Water Works Association (AWWA), pp. 248-258. New York, NY: The AWWA, May, 1979.

in the network (by nodes). With this information and the cost estimates for repair and replacement, managers can identify the impacts of different rehabilitation strategies and make better decisions.

Report Organization

The remainder of this report provides a description of the European research on the use of modeling techniques for proactive rehabilitation management and discusses how they have been used to improve rehabilitation decisions to optimize the operation and maintenance of water distribution and wastewater collection systems. It is organized into the following sections:

- Chapter 2 describes the existing non-hydraulic models and decision-support tools used in Europe to assess the condition of pipes and recommends the data necessary to predict future performance and to select rehabilitation options.

- Chapter 3 provides a summary of the key information and performance indicators used in Europe for rehabilitation planning.

- Chapter 4 recommends a framework for a database of key information on performance indicators.

Chapter 2
Summary of the European Experience Using Non-Hydraulic Models for Infrastructure Rehabilitation

In Europe, several universities, research centers, and private companies have developed various models for assessing rehabilitation and renewal needs for water and wastewater infrastructure. The objective of this chapter is to describe European non-hydraulic pipe assessment models and software applications, assess the significance of the factors influencing pipe failures, and recommend the type of data necessary to ensure valid and reliable decision making. Recommendations provided at the end of the chapter are based on a review of:

- the capabilities of eight pipe assessment software applications,
- the data required to run each model, and
- the data typically collected by more than 15 European water services.

The assessment of capabilities and data requirements was based solely on a review of European research and product literature.

Modeling Techniques to Predict Rehabilitation Requirements

The models and methods presented in this chapter were developed to assist managers who proactively plan infrastructure rehabilitation activities for water distribution and wastewater collection systems. An effective model should help a decision maker identify cost-effective rehabilitation strategies that result in an acceptable level of service. In its simplest form, the decision can be based on a cost comparison of two alternatives at any point in time:

- replace a pipe, incurring the replacement cost and whatever future costs are associated with the new line, or
- retain the existing length of pipe, at least for the time being, saving the replacement costs, but incurring the risk of greater future costs of repair, disruption of services, and damages.

However, managers may consider other factors in addition to costs such as risk of service interruptions, hydraulic capacity, reliability, water quality (for water distribution systems), risk of property damage, and environmental impacts. The analysis to support this decision, whether it involves only cost or other considerations, requires an estimate of the expected rate of breaks in the two pipes – the existing one and the potential replacement.

While there are many different approaches to predict failure rates and support rehabilitation planning, they typically incorporate one or all of the following major modeling techniques:

- Probabilistic or statistical methods that estimate a pipe's condition, defined as a probability of failure, based on a statistical analysis of the historical performance (break rate or expected life) of like pipes in similar conditions (operational or environmental). Statistical models can also be used to predict future system requirements by assuming that past break patterns will continue into the future.

- Deterministic methods that identify the best solution (i.e., pipe replacement date, least cost analysis, etc.) based, not on probability, but on a function of the initial pipe conditions and an understanding of how it modifies given changes in operational conditions, environmental conditions, or time.

- Heuristic methods that enable managers to apply expert judgement and weights to different decision criteria and to prioritize different rehabilitation strategies.

Regardless of the modeling technique, software applications or methodologies should help managers maintain information about the pipe network, assess current pipe conditions, prioritize repair options, and predict impact on future costs or system performance.

Summary of Models Available in Europe[1]

Eight models or methodologies designed to support rehabilitation planning were identified through a review of European research papers, company product literature, and interviews with European researchers and practitioners. An overview of each model is presented in the context of the following attributes:

- A description of the type of infrastructure assets covered – water and/or wastewater.
- A description of its capabilities to assess current pipe conditions and prioritize pipes for detailed evaluation and possible replacement, including
    - a point classification system for scoring observed defects,
    - a failure model to estimate break/burst rates for existing pipes,
    - a hydraulic model to calculate current capacity and vulnerability,
    - an economic model to estimate asset value, O&M costs for current pipes, and replacement costs,
    - a water quality model (for water distribution systems only) that estimates the concentrations of contaminants throughout the system and over time, and
    - a prioritization system to select critical pipes for rehabilitation.

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[1] The authors would like to acknowledge the invaluable contribution to the information presented in this chapter by Dr. Sveinung Saegrov, from the SINTEF Civil and Environmental Engineering, Department of Water and Wastewater, Trondheim, Norway. Much of the information presented in this section is based upon his research.

- A description of its capabilities to forecast future conditions, including
  - a failure model for estimating future break or burst rates and replacement dates,
  - an economic model to estimate future replacement and rehabilitation costs,
  - a hydraulic model to estimate future capacity and vulnerability,
  - a water quality model (for water distribution systems only) to estimate changes in distributed water quality based on network changes,
  - an economic model that estimates future asset values, future O&M costs and replacement costs, and
  - a tool to enable managers to compare future network rehabilitation scenarios.
- A description of its user interface and output options – GIS and graphical report generation.

Table 2-1 provides a summary of the models reviewed. The following sections provide a brief description of the eight models and, where available, provide references to additional information.

Table 2-1. European pipeline rehabilitation software applications/models reviewed

Model Name	Assets Covered		Country of Origin or Primary Use
	Water Distribution	Wastewater Collection	
AQUA-WertMin 4.0	X	X	Germany
AssetMap	X		France
EPAREL/EPANET	X		Norway and USA
Failnet	X		France
Gemini VA	X	X	Norway
KANEW	X		Germany and USA
KureCad	X	X	Germany
UtilNets (prototype)	X		Various European Countries

AQUA-WertMin 4.0 (Germany)

AQUA-WertMin was developed in Germany to assist infrastructure managers with the planning of TV-inspection, renovation and new construction strategies for water and wastewater networks. Based on the conditions observed during inspections, users enter pipe condition scores into the application. The software assigns one of the following six classifications to each pipe section in the network:

- Class 6: Excellent condition – no observed defects

- Class 5: Good condition – few defects observed, repair as needed
- Class 4: Fair condition – minor defects observed that will require repairs in long-term plan
- Class 3: Poor condition – defects observed that will require major repairs, but no renovation in the mid-term plan.
- Class 2: Very poor condition – defects observed that require major renovations, but not replacement in the near-term plan
- Class 1: Pipe failed – needs immediate replacement

The software then calculates the probability of a pipe section (or group of like pipe sections) transitioning from one condition class to the next lower (worse) class in the form of a Herz distribution.[2] To determine the transitional function, the program applies a survival model for groups of similar sewer sections, and a Weibull probability distribution function developed at the University of Karlsruhe for water distribution pipes.[3]

For sewer pipes, the survival function is based on the following equation:

$$S(t,a,b) = (a+1) / (a+\exp[b(t)])$$

Where:
t = years since the pipe was installed and is > 0
a = aging coefficient for the pipes grouped by age, material and condition at last inspection
b = failure coefficient for the pipes grouped by age, material and condition at last inspection

This equation is modified slightly for water distribution mains to:

$$S(t,a,b) = (a+1) / (a+\exp[b(t-c)])$$

Where:
c = years since the pipe was installed until its first rehabilitation.

The software calibrates the survival functions using data collected from the network inspection records to include year of pipe installation, year of inspection, pipe diameter, and pipe condition. AQUA-WertMin provides a forecast for the deterioration of pipe condition and future rehabilitation

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[2] Herz, Raimund K., Aging Processes And Rehabilitation Needs Of Drinking Water Distribution Networks, Journal of Water, SRT-Aqua Volume 45, 1996, pp 221-231.

[3] Eisenbeis, P., P. Le Gauffre, and S. Saegrov, Water Infrastructure Management: An Overview of European Models and Databases, AWWARF Infrastructure Conference, Baltimore MD, 2000.

needs. It enables users to compare the costs of different rehabilitation strategies based on an economic analysis of costs and time of repair.

AssetMap: Asset Maintenance Procedure (France)

AssetMap is not a software application, but an experimental modeling approach involving the use of probability and spatial analysis to determine break rates in existing pipes in the urban community of Lyon, France. Research[4] is carried out within the framework of a doctoral thesis jointly financed by the Générale des Eaux - Service Lyon Agglomération and the Association Nationale de la Recherche Technique.

The modeling approach utilizes a commercially available GIS system and statistical analysis software to accomplish the following five steps:

- Step 1: Forecast break rates for the network of pipes assuming that no rehabilitation will occur.

- Step 2: Conduct a statistical analysis of break rates using Poisson Regression for each group of pipe categories.

- Step 3: Present a spatial analysis of the break rates via a GIS using the statistical results of step 2, in order to identify other location factors for consideration (i.e., a visual display of break rates superimposed on a map displaying other geographical information such as buildings, roads, soil types, vegetation, other utilities, etc.).

- Step 4: Support decision making through the use of a multi-attribute utility analysis to rank critical pipes and evaluate different rehabilitation rates and criteria.

- Step 5: Forecast break rates by simulating various rehabilitation policies (rehabilitation spending and impact on prices).

In the first step, researchers develop a forecast of break rates without rehabilitation based on a model calibrated with historical data from the actual network. In the second step, researchers conduct a statistical analysis of break rates by Poisson Regression grouped by definition of pipe categories. Categories are defined for each length of pipe section with the same attributes (i.e., material, diameter, and location) as shown in Table 2-2.

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[4] Malandain J., Le Gauffre P., Miramond M. Organizing A Decision Support System For Infrastructure Maintenance: Application To Water Supply Systems, Proceedings. First International Conference on New Information Technologies for Decision-making in Civil Engineering. Montreal (Canada) 11-13 Oct. 1998, pp. 1013-1024. ISBN 2-921145-14-6.

Table 2-2. Relative incident rate ratios for sample pipe category attributes

Modeling Attribute	Attribute Value	Code	Relative Incident Rate Ratio for Attribute Value	95% Confidence Interval	
Pipe diameter (mm)	60-80	D0	1 (reference)		
	100-135	D1	0.77	0.68	0.86
	150-175	D2	0.36	0.28	0.44
	200-350	D3	0.16	0.12	0.21
	>=400	D4	0.06	0.03	0.12
Pipe material	Ductile iron	M0	1 (reference)		
	Grey cast iron	M1	9.99	7.91	12.6
Pipe location	Under sidewalk	E0	1 (reference)		
	Under roadway with light traffic	E1	1.13	0.98	1.30
	Under roadway with heavy traffic	E2	1.33	1.16	1.53
	Under roadway with very heavy traffic	E3	1.78	1.36	2.32

For each pipe attribute, researchers are able to determine a relative incident rate ratio (IRR) that compares the break rate for a standard reference value for a particular attribute (i.e., diameter between 60 mm and 80 mm, material is ductile cast iron, and location is under a sidewalk) to the failure rate for each other attribute (e.g., D1, M1, E1). The model uses as a reference the pipe category whose coded variables are D0, M0 and E0 to calculate a combined IRR for the pipe category based on the IRR for each individual attribute. This calculation can be shown by:

Pipe category 0 (D0, M0, E0) has a combined IRR =1*1*1 = 1,

Pipe category i (D3, M0, E0) has a combined IRR = 0.16*1*1 = .016,

Pipe category j (D3, M1, E0) has a combined IRR = 0.16*9.99*1 = 1.60.

The researchers found the main advantage of the Poisson Regression model is that it provides processed data that can easily be used for decision-support since the results provide a prioritized list of critical pipes. This means that if the only basis for renewal is structural reliability, then annual rehabilitation and leak detection programs can focus on just a few of the 40 categories in the model that have the highest IRR. Table 2-3 shows sample break rates modeled for 'critical' categories based on the experience in Lyons:

Table 2-3. Sample break rates for critical pipe section attributes from Lyon, France

Category of Pipe Section	Modeled break rate/km year
C (D0, Mat1, E3)	0.343
C (D1, Mat1, E3)	0.263
C (D0, Mat1, E1)	0.219

In step 3, researchers input break rate information into a GIS system to conduct a spatial analysis of break rates in order to identify other geographic factors to be considered in rehabilitation planning. An example spatial analysis of break rates is shown in Figure 2-1.

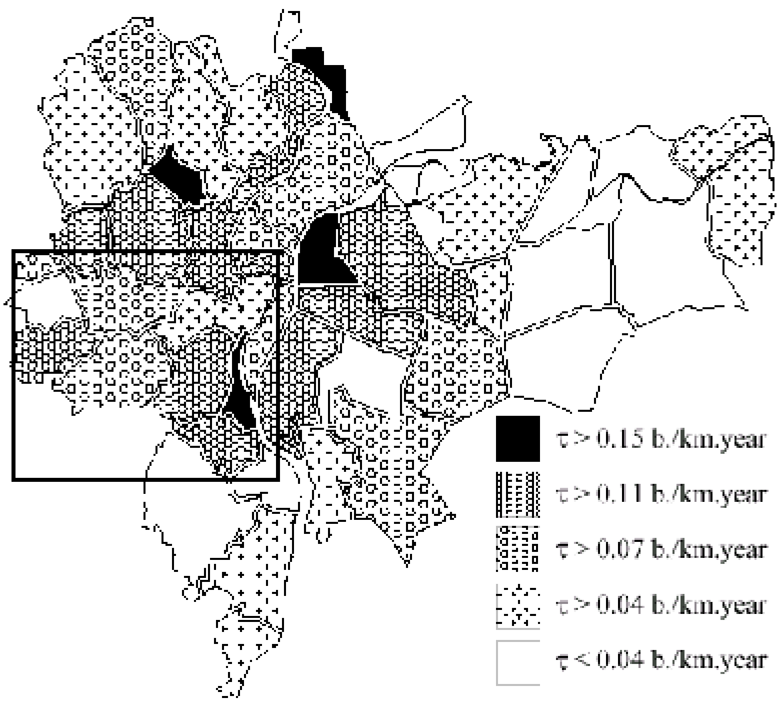
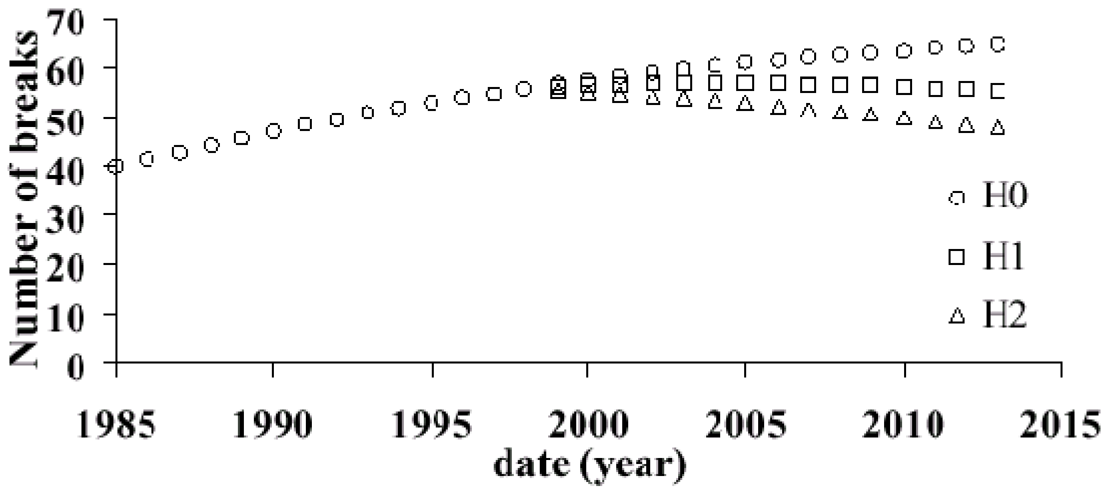


Figure 2-1. Spatial analysis of break rates for water mains in Lyons, France.

In step 4, researchers use a multi-attribute utility analysis to identify the most critical pipes, not only on the risk of failure as determined in step 2, but also on the potential impact that particular pipe failure will have on the system. For example, researchers combine the pipe failure rate with the number of customers served by the pipe to determine an overall vulnerability risk criterion to prioritize renewal planning. A specific approach related to risk mitigation is currently under development.

In step 5, researchers use a statistical analysis to develop forecasts of break rates as a function of time for various rehabilitation policies (rates and rehabilitation scenarios). On one part of the Lyons network studied, researchers projected the number of future breaks from 1999 onwards for three different rehabilitation scenarios, as shown in Figure 2-2.



H0 = Projected pipe break rate without any pipe replacements or rehabilitation.
H1 = Projected pipe break rate with a random renewal of 1% of mains for 15 years.
H2 = Annual renewal of 1% of small diameter pipes below roadways for 15 years.

Source: Malandain J., Le Gauffre P., Miramond M., Organizing a Decision Support System for Infrastructure Maintenance: Application to Water Supply Systems. Journal of Decision Systems, Volume. 8 – N°2/1999, pp. 203-222, 1999.

Figure 2-2. Evaluation of different rehabilitation policies on pipe break rates in Lyons, France.

Researchers compare projected break rates between a strategy of non-intervention, a plan of random renewal of 1% across all pipe mains for 15 years, and an annual renewal of 1% of small diameter pipes below roadways for 15 years. At the time of this paper, researchers were still refining this model.

EPAREL and EPANET (Norway and US)

The Norwegian research institute, SINTEF, has developed a water quality modeling tool, EPAREL, that builds on a USEPA tool, EPANET, to assess the risk of a network failure that would interrupt the supply of quality water to any customer. EPANET is a computer program that performs extended-period simulation of hydraulic and water quality behavior within pressurized pipe networks. EPANET tracks the flow of water in each pipe, the pressure at each node, the height of water in each tank, and the concentration of a chemical species throughout the network during a simulation period consisting of multiple time steps. In addition to calculating water age, the model can also simulate source tracing within the network. EPANET runs on Microsoft Windows® and provides an integrated environment for entering network data, running hydraulic and water quality simulations, and viewing the results in a variety of formats. These include color-coded network maps, data tables, time series graphs, and contour plots.

EPAREL builds on the EPANET model by applying statistical models, based on a modified "Non-Homogeneous Poisson Process" and a Weibull function, to calculate the failure probability for each pipe section in a network. The probability of failure is modeled for groups of pipes characterized by material, construction year, water quality, surrounding soil and diameter. For those pipes with a record of very few failures (i.e., large diameter pipes), the failure probability is estimated from professional judgement.[5] The models are being tested with data from Norwegian municipalities.

Failnet: Analysis and Forecasting of Water Network Failures (France)

This methodology of analyzing and forecasting water pipe failures has been applied at several urban and rural water services in France, including Bordeaux, Alsace, and Charente-Maritime.

It consists of three steps:

- Analysis of historical failure records using a proportional hazard model. The system analyzes historical data, valuates factors that influence failures, and identifies factors that maximize the likelihood of failures.

- Definition of survival functions based on a Weibull Model. The system integrates the failure relationships determined in the previous steps with information on the pipes' current conditions to calculate the probability of a group of pipes (grouped by material and current condition) to survive at a given condition level during a given time period.

- Forecasting the number of failures for a defined period using a Monte-Carlo method. The system then forecasts the number of failures from the survival functions for each group of pipes (materials and current condition). This forecast can be used in combination with a

[5] Røstum J. and Schilling W., Predictive Service-Life Models Used for Water Network Management, 14th EJSW, Dresden, 8-12 September 1999.

hydraulic reliability model, in an economic model, or alone as one of the rehabilitation criteria.

Gemini VA (Norway)

In Norway, almost all the major municipalities use the Gemini VA information system to manage water and sewer network data.[6] This makes the exchange of key numbers from the same data platform possible. The system enables the integration of pipe failure information with a GIS interface. The user interface is a computer-generated network map, from which a user can select a single pipe, and the system will retrieve the required data from the database.

The system can store network, pipe, failure, repair, and maintenance data. The property tables store position, depth of pipe nodes, diameter, pipe material, joint system, and construction year information. The system also stores information about pipes that were replaced or taken out of service.

Gemini contains a module to record operation and maintenance information. The module enables users to record a chronological operations history of the water and sewer network, including:

- Incidents (bursts, leaks, operational interruptions),
- Conducted work (repairs, TV inspections, high pressure flushing, etc.),
- Secondary failures,
- Network condition and reasons of failures, and
- Quality considerations.

Gemini VA also includes a report generator that can be used for statistical analyses and graphical presentations.

KANEW: Exploring Rehabilitation Strategies (Germany and US)

KANEW is a cohort survival model for infrastructure that has been developed at Karlsruhe University to predict future rehabilitation needs for water infrastructure. Based on this approach, Dresden University of Technology developed a software application in a research project sponsored by the American Water Works Association Research Foundation (AWWARF). It is available in Microsoft Access® format to AWWARF subscribers. KANEW predicts when select pipe sections will reach the end of their service lives, differentiated by date of installation and by type of pipe sections with distinctive life-spans.

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[6] Saegrov, S., Selseth, I., and Schilling W., Management of Sewer System Data in Norway. EWPCA Symposium, “Sewerage Systems – Costs and Sustainable Solutions.” 4-6 May, 1999 in conjunction with 12th IFAT 1999 Exhibition, Munich, Germany.

The system assumes service-life to be a random variable, starting after some time of resistance and being characterized by a median age and a standard deviation, or age that would be reached by a certain percentage of the most durable pipe section. The user can choose the parameters of the Herz-distribution. Predictions are based on optimistic assumptions of service-lives that are derived from failure and rehabilitation statistics for different types of pipes. The cohort survival model of KANEW is a tool for exploring network rehabilitation strategies.[7] KANEW contains a network inventory module, a failure and break forecasting module, an economic data module and a strategy comparison module. Figure 2-3 shows relationships between the different KANEW modules.

KureCAD (Finland)

The Viatek Group in Finland developed a tool, KureCAD, which uses GIS to manage sewer pipe rehabilitation. The system can store information on all infrastructure assets, prioritize the rehabilitation of pipes, and provide the necessary documents to implement the rehabilitation. The KureCAD user interface is based on a map of the network. If maps are not digitally available from the outset, hard copies can be scanned into the system or manually digitized. Using the GIS interface, a user can recall a wide variety of information, including location, size, and type data for manholes, valves, and fire hydrants.

To ensure consistency for data collection during field inspections and maintenance, the KureCAD system provides instruction. Once the KureCAD system contains all the necessary data, it enables managers to assess and prioritize system conditions. For each pipe section, the system enables users to record three basic types of data:

- Structural condition (strength and shape),
- Functional condition (its ability to transport water), and
- Leakage rates (estimated leakage from the pipe).

For each type, users can employ data from internal inspections or maintenance records to summarize the pipe's condition by assigning a score from 1 (good, no repairs required) to 4 (very bad, needs to be repaired immediately). Users can also rate each pipe using other factors entered by the user. The system records whether the entered data is based on estimates or actual inspections. The KureCAD system then combines all of the condition scores into one condition index and converts it to a GIS display.

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[7] Herz, R. Aging Processes And Rehabilitation Needs Of Drinking Water Distribution Networks, Journal of Water, SRT-Aqua Volume 45, 1996, pp 221-231 and HERZ, R. Exploring Rehabilitation Needs and Strategies for Water Distribution Networks. Journal of Water, SRT-Aqua Volume 47, 1998, pp 1-9.

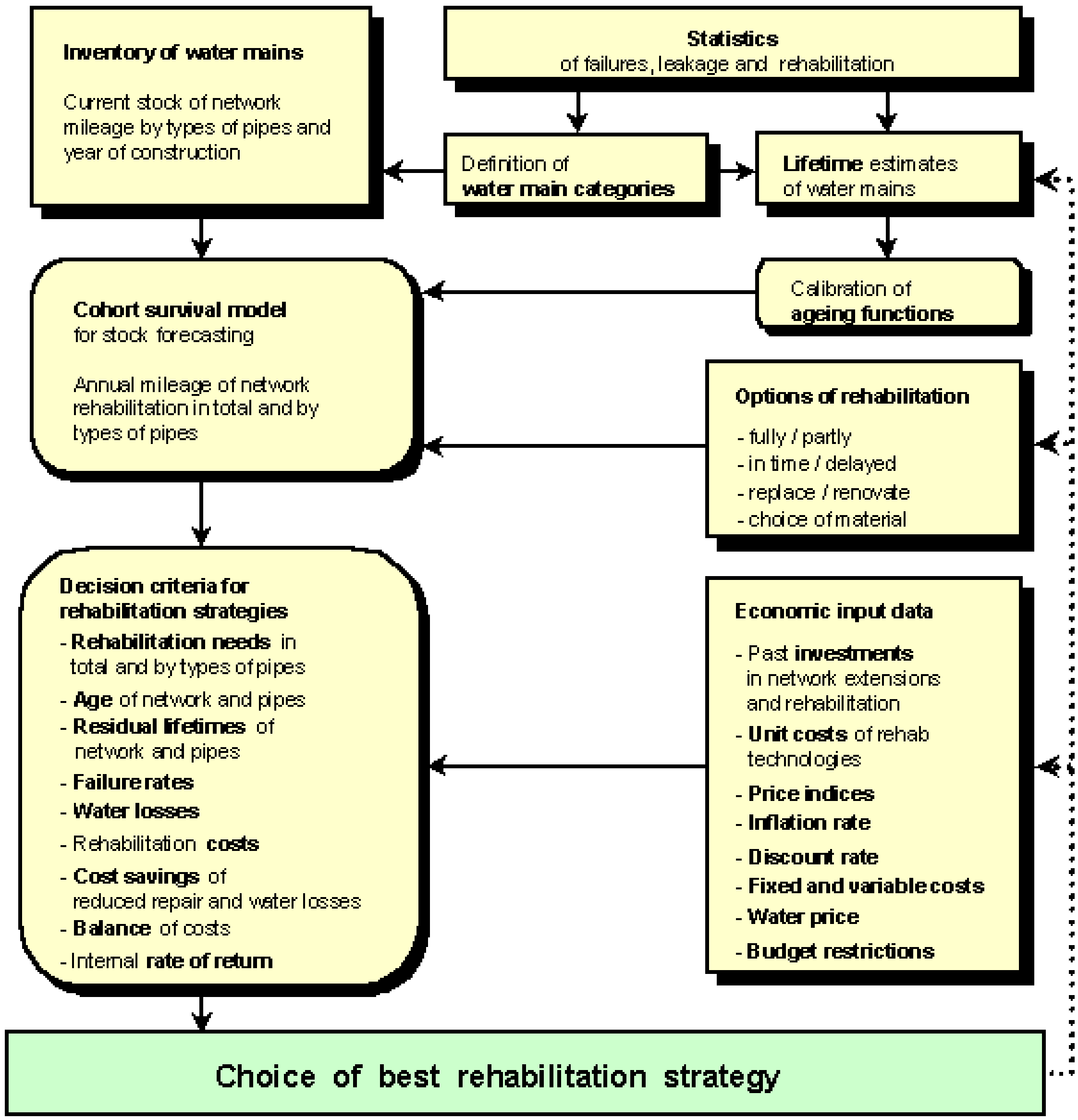

Figure 2-3. KANEW approach to rehabilitation planning.

Once the KureCAD system is populated with all the required data, managers are equipped with the information needed to assess the condition of pipes in the network, prioritize pipes for rehabilitation, identify alternative rehabilitation options, and determine associated costs. Finally, KureCAD can store and generate the planning and design documentation required by the water service to begin rehabilitation. This includes detailed site maps, detailed construction specifications, and contract conditions.

UtilNets (Various European Countries)

UtilNets is a prototype of a reliability-based, decision-support system for the maintenance management of underground utilities. It performs current-condition assessments and reliability-based life predictions of pipes, and determines the consequences of maintenance decisions. At the time of this study, the software was in a prototype phase and only assessed gray and ductile cast-iron water mains.

In contrast to models that attempt to predict pipeline failure based on service failure statistics and using data from specific systems, the UtilNets model is based on physical models of the degradation process. It calculates the remaining service life of single pipe sections and water networks. The model considers internal and external corrosion of cast iron and ductile iron pipes. Since the rate of corrosion varies to a large extent along the length of a pipeline, the model utilizes a probabilistic distribution function of corrosion. UtilNets also considers external load conditions to include soil weight, traffic load, uneven foundation (pipe acting as a "beam"), pipe wall temperature, and frost action. The load variation along a pipeline is modeled using a probabilistic function, and the extreme values are determined from "worst case" estimates.

UtilNets classifies pipe components as links and segments. A link is the length of pipe between two nodes. A node may be a connection of pipes, a network structure such as a reservoir, or just a change of basic network characteristics (e.g., pipe material or age). A segment is a part of a link and links may be divided into segments for various reasons (e.g., if a main road crosses the link, the part under the road is considered a separate segment). A long pipe can be divided into segments of equal length.

The system consists of a GIS-based user interface and results are presented as thematic maps and tables. It also utilizes a decision-support system to support rehabilitation planning by ranking each pipe segment in the whole network on a basis of need for rehabilitation. It provides a forecast on the aggregate structural, hydraulic, water quality, and a service reliability profile of the network, together with an assessment of the required rehabilitation expenditures. UtilNets attempts to answer questions such as:

- What is the structural life expectancy of a specific water main segment?
- What is the probability that the pressure at the end of a specific water main segment will be adequate in 3 years?
- Which pipe segments will cause dirty water problems?
- What is the optimal rehabilitation scheme for a specific water main segment?
- What should be the current rehabilitation budget for the utility?
- What should the future rehabilitation budget for the utility be in 5 or 10 years time?

UtilNets consists of eight modules divided into three groups:

- Analysis Modules:
  - Structural Reliability Module (M1)
  - Hydraulic Reliability Module (M2)
  - Water Quality Reliability Module (M3)
  - Service Reliability Module (M4)
- Optimization Modules:
  - Options and capital costs for water main rehabilitation (M5)
  - Non-quantifiable consequences of failure ("Risk Module", M6)
  - Prioritization of water main rehabilitation (M7)
- Background Information Module:
  - Network reliability (M8)

STRUCTURAL RELIABILITY MODULE (M1)[8]

This module assesses the structural performance in service over time for each selected pipe segment. First, it determines the deterioration caused by corrosion. The resulting decrease of resistance is compared to the internal water pressure and external loads (soil, temperature, traffic etc.). The system develops an estimate (probability distribution) of structural reliability by monitoring, as a function of time, the magnitude of the difference between the operating characteristics of the water main (pit depth, stress and stress intensity factors) and the operating limit (wall thickness, strength and fracture toughness). When the operating characteristics reach a prescribed limit, the pipe, link, segment or whole network begins to operate unsatisfactorily and this qualifies as failure.

Structural analysis is performed in two steps: deterministic and then stochastic. The deterministic approach calculates all the constant or frequently applied loads, sums them according to the direction in which they operate, and compares them with remaining stress and strain carrying capacity of the pipe. This can be compared to the conventional process of designing a pipe from a list of known and given loading conditions. The deterministic sub-modules are:

[8] The module capabilities are taken from the following research paper and not from an actual review of the software. Hadzilacos Th., Kalles D., Preston N., Melbourne P., Eimermacher M., Kallidromitis V., Frondistou-Yannas S., Saegrov S., "UTILNETS: A Water Mains Rehabilitation Decision Support System", Computers, Environment and Urban Systems, special issue on Urban Knowledge Engineering, accepted.

- Loads: computes present values for loads and stresses, and
- Safety Factors: based on the loads and stresses, a first estimate is computed for each selected segment.

For several features, such as internal pressure, a ratio between the strength of the pipe segment and the loads is given as a safety factor. The user might focus, for instance, on the "worst" segments for the next steps.

Due to the degradation of the pipe, there is a point in time where the probability of different loads being applied together at the same moment will cause a failure. From this point on, the system considers the probability and randomness of these loads, their type and frequency, and the future degradation of the pipe. The pipe degradation previously computed is compared with a stochastic process of load events (e.g., heavy truck traffic above a pipe segment or cold weather).

The module also contains two stochastic sub-modules:

- Structural Reliability: computes the structural life expectancy for each selected segment by estimating the probability of coincidences of external loads, and
- Structural Reliability Fast: Here, only the first year where risk for the pipe rises above zero is computed. (In contrast, the full version computes a curve showing the increasing risk from zero to one over time.) If only aggregated data is needed for the priority of rehabilitation, this fast version is recommended.

HYDRAULIC RELIABILITY MODULE (M2)[9]

This module assesses the hydraulic performance of a water main in service by comparing its state of behavior, as a function of time, to each one of two limit states. These limit states are defined as the maximum demand requested, and a specified minimum operating pressure. The method is similar to the one adopted for the structural sub-module and is essentially based on the analysis of interference data. An estimate of hydraulic reliability is obtained by monitoring, as a function of time, the magnitude of the interference between the operating characteristics on the water main (friction factor, head loss, etc.) and the operating limits (maximum flow and minimum pressure).

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[9] Ibid

WATER QUALITY RELIABILITY MODULE (M3)[10]

This module takes into account effects that pipe condition can exert on water quality, i.e., the inside surface of the pipe can corrode and the corrosion products can pass into the water. The module is built around pre-existing research available in the literature on the interaction between pipe materials and water quality parameters.

SERVICE RELIABILITY MODULE (M4)[11]

This module combines all the reliability results given above: structural, hydraulic, and water quality. It is defined by the combined probability of a segment suffering none of these failures in a given year. This is then calculated into the future until a failure or probability above zero occurs.

OPTIONS AND CAPITAL COSTS FOR WATER MAINS REHABILITATION (M5)[12]

This module generates a list of technically feasible rehabilitation solutions for the water mains with a structural, hydraulic, or water quality failure predicted by one of the above modules. Technical rules, flow carrying comparisons of the different rehabilitation techniques, and scheme details that might preclude some remedial measures are taken into account. For these solutions, the net present value of cost is derived in order to select the technically feasible option with minimal cost.

NON-QUANTIFIABLE CONSEQUENCES OF FAILURE ("RISK MODULE," M6)[13]

This module assesses the non-quantifiable consequences of a pipe failure. A water pipeline failure can deprive sensitive customers of supply, cause the collapse of other utilities, produce damage to streets and other structures, or any combination of these. These outcomes must be taken into account when assessing priorities for water main rehabilitation. The module ranks each consequence both individually and in combination with the others. The ranking is shown using an arbitrary scoring scheme, where a large number indicates a grave consequence. The system generates an overall hazard score for each failing link based on the risk score for each of the identified risk parameters. The system is able to select only those consequences that derive from the related cause of failure; e.g., hydraulic failure does not have consequences for damage to other utilities, whereas structural failure will have consequences for both sensitive customers and also damage to streets.

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[10] Ibid

[11] Ibid

[12] Ibid

[13] Ibid

PRIORITIZATION OF WATER MAIN REHABILITATION (M7)[14]

This module develops a prioritized list of all failed links for rehabilitation based on a function of hazard potential and rehabilitation cost.

NETWORK RELIABILITY (M8)[15]

This module assists users in understanding the reliability of a supply system without doing numerous iterations on a complete hydraulic model with a complex network solver. Water distribution mains in a network often have large amounts of redundancy, and although there is rarely true hydraulic redundancy, there may be a measure of inter-connectivity that rehabilitation planners can exploit. To assist with this, the system assesses two reliability measures: demand point connectivity, which is the probability of complete isolation of each demand point from a water source point, and adequacy of flows at each demand point. Since complete hydraulic calculations and conventional 24-hour simulations are not undertaken within UtilNets, a true adequacy of flow cannot be provided. An estimated "adequacy of flow" is determined based on rules from which the user may select a short list for subsequent analysis in a proprietary hydraulic model.

GIS CAPABILITIES

The UtilNets system uses a GIS to store actual location for all parts of the underground network (e.g., pipes, valves, etc.). Thus, it can correlate the pipe location with:

- soil types and temperature data to better estimate corrosion rate;
- existing ground structures, such as roads, to estimate loads on pipes; and
- consumers information, such as hospitals, to estimate consequences of failure.

The GIS also allows the user to selectively examine parts of the network based on their location with reference to streets, cities, or other landmarks.

Researchers do stress that at the time of this report, the current prototype of UtilNets is too rigid, too complex, and may require amounts of data that may be unaffordable to collect and enter into the system. For this reason, researchers are involving more utilities from across Europe to help design a commercially available version of UtilNets.

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[14] Ibid

[15] Ibid

Data Requirements

Based on a review of product literature and a 1999 study[16] by Eisenbeis, Le Gauffre, and Saegrov, required data was classified by each of the European models as "required data," "highly significant data," and "useful data" (Table 2-4). All the software applications require, at a minimum, the following five variables for each pipe segment: age, length, material, number of recorded breaks, and pipe diameter. Other variables used by the models include pipe condition, soil condition, traffic loading, or the location of the pipe.

Table 2-4. Data requirements for European pipe rehabilitation models

Data Description	AQUA-WertMin	AssetMap	Failnet	Gemini	KANEW	KureCAD	EPANET/ EPAREL	UtilNets	Summary
Pipe material	x	x	x	x	x	x	x	x	x
Pipe age	x	x	x	x	x	x	x	x	x
Pipe length	x	x	x	x	x	x	x	x	x
Number breaks/bursts	x	x	x	x	x	x	x	··	x
Pipe diameter	x	··	··	··	··	x	x	x	x
Soil data (type varies)	··	··	··	··	··	··	x	x	··
Traffic data (type varies)	··	··	··	x	··	··	·	x	··
Pipe location (type varies)	·	··	··	x	·	x	·	·	··
Water pressure	·	··	·	·	·		·	··	··
Failure/defect type	··		··	x	··	·	··	··	··
Pipe condition	x	··		x	··	··	·		··
Type of corrective action	··			··	··	··			··
Type of joints	··		·	·	·	··	·	··	·
Leakage rates	·	·	·	·	··	··		·	·
Date pipe repaired	x	·		·	·	·			·
Date pipe video inspected	x			·	·	·		·	·
Economic data	··	·		·	·	··		·	·
Rehabilitation cost	··	·		·	·	··		·	·
Utility locations				·	·	·		·	·
Tree locations				·	·	·		·	·
Elevation contours				·	·	·		·	·

Notes:
- x required data (according to previous studies or product literature)
- ·· highly significant data (according to previous studies or product literature)
- · useful data (according to previous studies or product literature)

[16] Source: Eisenbeis, P., P. Le Gauffre, and S. Saegrov. Water Infrastructure Management: An Overview of European Models and Databases, AWWARF Infrastructure Conference and Exhibition Proceedings, Baltimore, Maryland, 2000.

Data Typically Recorded by European Water and Wastewater Services

As can be seen from the models described in this report, many parameters must be recorded and analyzed to assess the condition of water distribution and wastewater collection systems to plan the most effective maintenance and rehabilitation measures. Although most water service companies collect much of this information as part of their standard operating procedures, European researchers and practitioners point to the high cost of collecting additional data as a major barrier to extensive use of modeling and computer applications.[17] However, no specific study was found to quantify this cost.

Table 2-5 presents the results of a study[18] that summarized the data European practitioners collected in nine cities in Europe (Lyon and Bordeaux in France, Lausanne in Switzerland, Reggio Emilia in Italy, Bristol in the United Kingdom, Oslo and Trondheim in Norway, Dresden and Stuttgart in Germany). These cities were chosen as sample sites and may not be completely representative of the data collected by an "average" service.

Table 2-6 summarizes a study[19] on the data collected by five Swedish water services. As can be seen from the table, none of the Swedish water services collected information on water pressure, whereas most of the water services in the nine European cities mentioned above did collect that information.

Analysis of the Factors Contributing to Pipe Failure Rates

In Europe, as well as in the US, there has been much research on the factors that contribute to pipe failures, with the goal of developing or improving predictive planning models. However, this research has shown that developing models which accurately predict pipe failures is a complex process because there are many factors that affect failure and influence maintenance decisions. Since data collection can be very expensive, it is important to assess the significance of the factors that affect failure rates, so as to identify the important data to collect.

The factors affecting pipe failure rate can be either time-dependent or static. Pipe diameter or pipe material are examples of static (i.e., will not change over time) factors that affect pipe deterioration.

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[17] Stahre, Peter., and Gerald Jones, Diagnosis of Urban Water Supply and Sewerage Systems: Presentation of the Work of COST C3. COST Action C3 Workshop Proceedings, pp. 112-121. Brussels, Belgium: European Commission, 1996.

[18] Source: Eisenbeis, P., P. Le Gauffre, and S. Saegrov. Water Infrastructure Management: An Overview of European Models and Databases, AWWARF Infrastructure Conference and Exhibition Proceedings, Baltimore, Maryland, 2000.

[19] Sundahl, Ann Christin. Diagnosis of Water Pipe Conditions, Lund University, Department of Water Resources Engineering, Lund, Sweden, 1996, ISSN 1101-9824.

Table 2-5. Data collection efforts by European water services

Description of the Data Collected	Lyon	Bordeaux	Lausanne	Reggio Emilia	Bristol	Oslo	Trondheim	Dresden	Stuttgart
Years that recorded break date collected	1993 - > 1982 - >	1951 - > 1970 - >	1926 - >	1994 - >	1995 - >	1976 - >	1988 - >	1994 - >	1978 - >
% pipes with age recorded	S: 62% C: 21% (2)	85%	99%	*NA*	~ 50% (5)	99%	95%	50%	99%
% pipes with length of pipe segments recorded	100%	100%	100%	100%	100%	100%	100%	100%	100%
% pipes with material recorded	S: 98% C: 50% (2)	95%	99%	Su: 86% Di: 95% (1)	51%	100%	95%	90%	99%
Total length of mains (km)	3000	3000	700	890 (1) (su. + di.)	7694	1600	750	1800	1326
% pipes with pipe diameter recorded	100%	99%	100%	100%	95%	100%	100%	90%	100%
% pipes with soil information recorded	100%	60%	0%	*NA*	100% (6)	*Thematic maps*	*Thematic maps*	Soil 60% Bedding 20%	31%
% pipes with traffic information recorded	100%	100%	0%	*NA*	Partly	0%	0%	0%	0%
% pipes with pipe location recorded	98%	90%	0%	100% (3)	100%	100%	100%	50%	100%
Approximate number of pipe segments files	50 000	10 000	7 000	15 886	76 161	37 000	7 000	*NA*	16531
% pipes with joint type recorded	*NA*	10%	50%	*NA*	11%	*NA*	80%	60%	100%
% pipes with water pressure recorded	20% *on going*	95%	100%	(4)	*NA*	100%	100%	100%	100%

Source: Eisenbeis, P., P. Le Gauffre, and S. Saegrov. Water Infrastructure Management: An Overview of European Models and Databases, AWWARF Infrastructure Conference and Exhibition Proceedings, Baltimore, Maryland, 2000.

Notes: (1): Su: supply, Di: distribution; (2) C: City, S: Suburbs; (3) average of total length, one orthogonal measurement from the properties each 120m of length; (4) pressure spot measurements, permanent district flow metering; (5) 50% known, others estimated from pipe material; (6) corrosivity and fracture potential class. NA = not available.

Table 2-6. Types of data collected by Swedish water services

Description of the Data Collected	Malmo	brebro	Eskilstuna	Vasteras	Lulea	Number Collecting Data
Type of leak/failure	1	1	1	1	1	5
Date of leak/failure	1	1	1	1	1	5
ID number for pipe node	1	1	1	1	1	5
Pipe diameter	1	1	1	1	1	5
Date of pipe installation	1	1	1	1		4
Cause of leak/failure	1		1	1	1	3
Description of corrective action taken		1	1	1		3
Cost of corrective action		1	1	1		3
Length of pipe segments	1	1	1			3
Date of last repair	1	1	1			3
Street name	1		1	1	1	3
Pipe material	1	1		1	1	2
Pipe condition				1		1
Soil information		1				1
Fill type		1				1
Traffic information		1				1
Depth of pipes		1				1
Type of joints		1				1
Water pressure						0

Pipe age, temperature, soil temperature and water content, and observed pipe defects are examples of random, time-dependent factors that may influence the breakage rate of underground pipes.[20] In addition to being classified as time-dependent or static, the factors influencing pipe failures can be classified as shown in Table 2-7.

The following sections summarize various European research papers that analyze the significance of the factors that influence pipe failure and leak rates.

Influence of Pipe Age on the Structural Deterioration of Pipes

At the heart of most rehabilitation models is the premise that as pipes get older, they require more maintenance and repairs. Therefore, many rehabilitation plans have often been based solely on the age of the pipe. As in the US, European research[21] has shown

[20] Kleiner, Y., and B. Rajani. Considering Time-dependent Factors in the Statistical Prediction of Water Main Breaks. Ottawa, Ontario, Canada: Institute for Research in Construction, National Research Council Canada, Infrastructure Management Conference Proceedings, American Water Works Association Research Foundation, Baltimore, MD. 2000.

[21] Sundahl, Ann Christin. Diagnosis of Water Pipe Conditions, Lund University, Department of Water Resources Engineering, Lund, Sweden, 1996, ISSN 1101-9824.

Table 2-7. Factors that influence pipe failure rates

Category of Factors that Influence Pipe Failure Rate	Factors
Pipe section factors	pipe material
	pipe diameter
	joint type
	pipe age
	pipe depth below surface
	pipe condition (wall thickness, defects, etc.)
Operational and maintenance factors	operating pressure (water distribution)
	nature and date of last failure (e.g., type, cause, severity)
	nature of maintenance operations (e.g., TV inspections, pipe cleaning, cathodic protection)
	nature and date of last repair (e.g., type, length)
	water quality
	construction method (e.g., fill type)
Environmental and climate factors	soil type
	soil temperature or frost depth
	rainfall
	soil moisture content
	temperature
	traffic and loading

that pipe age is significant, but not the only indicator of pipe failure rates. Other factors, such as current condition, diameter, and location contribute to the significance of pipe age.

For example, Figure 2-4 shows the leak frequency distributed according to pipe age for gray cast iron (GCI) pipes based on a study[22] of Swedish water companies. Swedish researchers studied leak frequencies for five municipalities over a five-year period and determined that the number of leaks in GCI pipes increased with pipe age up until the pipes were about 30 years old. After this, and until the pipes were about 80 years old, there was no significant correlation between leak frequency and pipe age. The same pattern also emerged when each municipality was studied separately.

[22] Ibid.

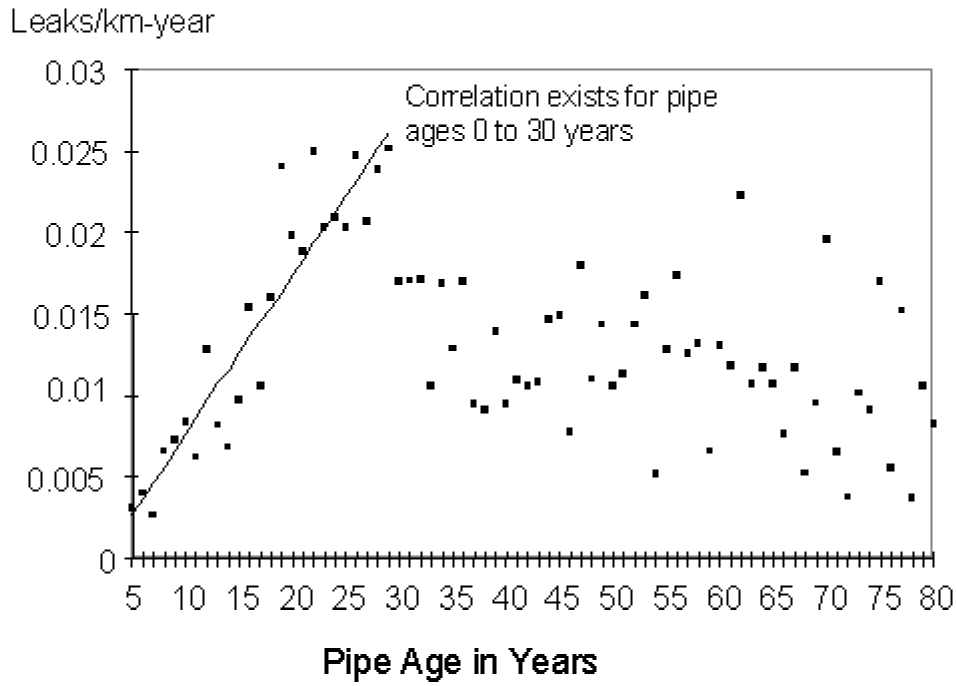


Figure 2-4. Leak frequency versus pipe age for GCI water distribution pipes measured over a five-year period for Malmo, Sweden.

Figure 2-4 shows that, on average, a water distribution pipe that is 50 years old can have a lower leak rate than a pipe that is 30 years old.

European research has shown that pipe age is a fairly good indicator of pipe breaks in wastewater collection pipes. Swedish researchers conducted a study[23] in Malmö, Sweden to investigate factors that influence changes in the structural condition of wastewater pipes. The resulting study presents a model for the structural deterioration of sewer pipes over time based on the team's observations (TV inspections) of the changes in pipe defects over an average of 5-year intervals for 5800 meters of concrete sewer pipes, 4200 meters of PVC pipe, and 1200 meters of PE pipe. As shown in Figure 2-5, they concluded that pipe age, as grouped into two age categories by installation date, was a good indicator of failure rate. Pipes installed before 1950 (class O pipes) demonstrated a higher change in observed damage over a 7-year period than pipes installed after 1950 (class N pipes).

[23] Lidström, Viveka, Diagnos Av Avloppsledningars Kondition (The Diagnosis of the Condition of Sewer Pipelines), Rapport 3194, Institutionen för Teknisk Vattenresurslära, Lunds Tekniska Högskola, Lunds Universitet, Lund, Sweden,1996.

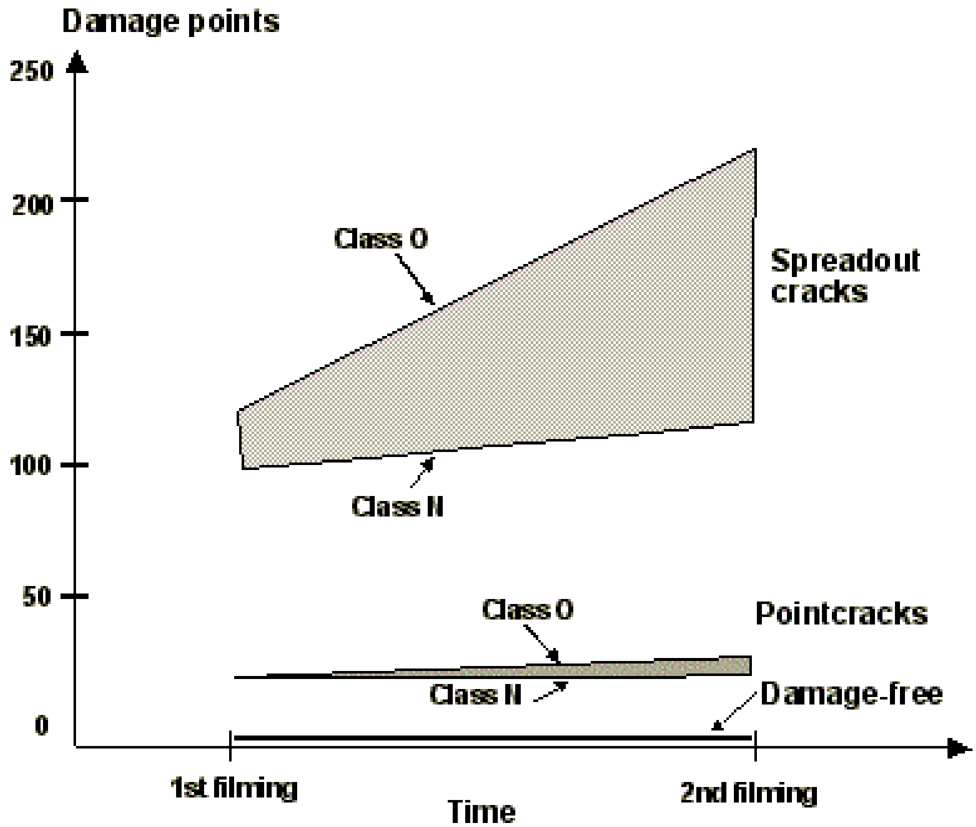


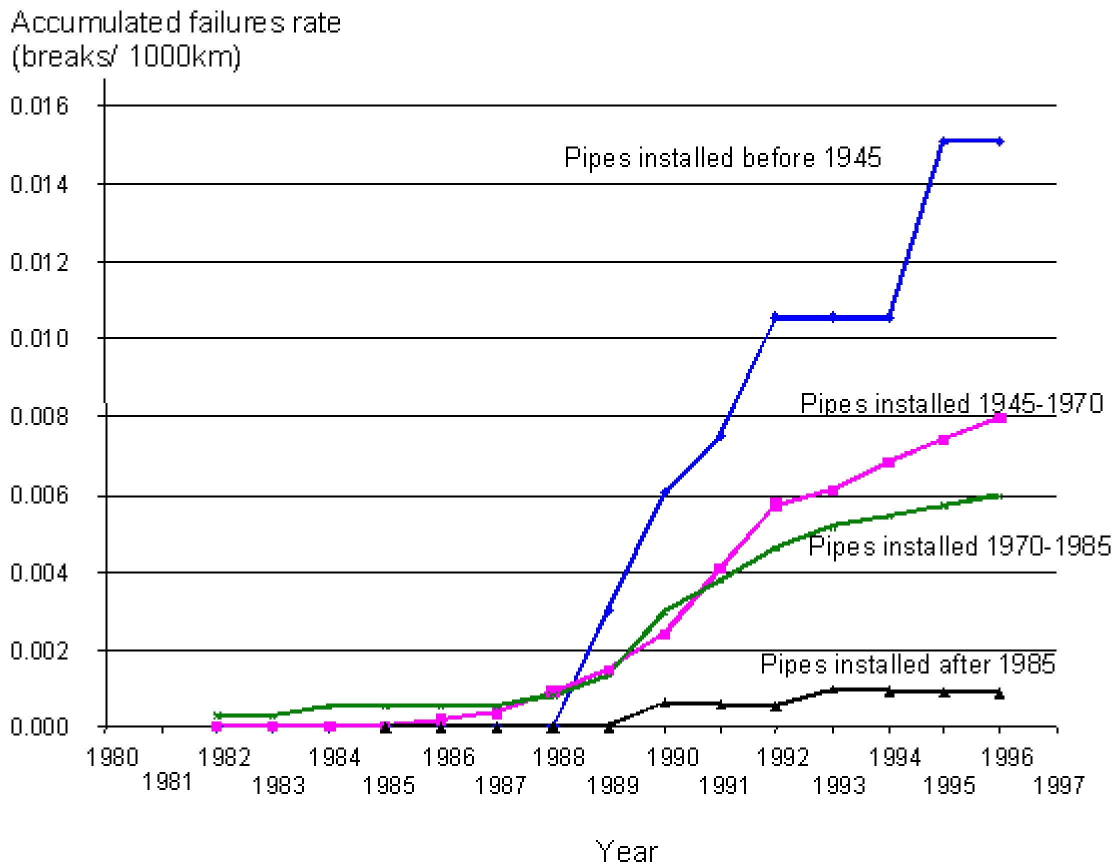
Figure 2-5. Change in observed damage over 7 years for sewer pipes installed before 1950 (class O) and sewer pipes installed after 1950 (class N) for Malmo, Sweden.

Results from a Norwegian study also supported the significance of pipe age in predicting failure rates for sewer pipes. Figure 2-6 shows that the older the pipe, the worse the condition. However, researchers did not conclude that this was due solely to pipe age.

Influence of Pipe Materials on Pipe Failure Rates

European research has shown, similar to research in the US, that failure rates and leak rates differ for various pipe materials. Table 2-8 contains an analysis of relative failure rates for different pipe materials, as compared to the failure rate of gray cast iron pipes based on a study[24] of the information collected from and the software tools used by European water

[24] Eisenbeis, P., P. Le Gauffre, and S. Saegrov. Water Infrastructure Management: An Overview of European Models and Databases, AWWARF Infrastructure Conference and Exhibition Proceedings, Baltimore, Maryland, 2000.



Source: Saegrov, S., Selseth, I., and Schilling W., Management of Sewer System Data in Norway. EWPCA Symposium, "Sewerage Systems – Costs and Sustainable Solutions." 4-6 May, 1999 in conjunction with 12th IFAT 1999 Exhibition, Munich, Germany.

Figure 2-6. Accumulated failures versus pipe installation year for concrete sewer pipes in Trondheim, Norway.

services. In Reggio Emilia (Italy), the failure rate is larger for gray cast iron and asbestos cement (AC) pipes. In this case, the average age of the pipe is not taken into account. Researchers note that the cause of the failure rate for GCI pipes decreasing from 1994 to 1996 may be due to a policy change that resulted in decreasing water pressure in the distribution systems. For Bordeaux, ductile iron and GCI pipes are compared. Even after eliminating the influence of age, it shows that GCI pipes break more than ductile iron pipes. The table also shows that, in Norway, asbestos cement and unprotected ductile iron pipes are more vulnerable than GCI.

Table 2-8. Sample relative failure rates* for different pipe materials used in water distribution systems

	Reggio Emilia			Failnet	NTNU/SINTEF		
	1994	*1995*	*1996*	*Bordeaux*	*Trondheim 1988-1996*	*Oslo 1976-1998*	*Bergen 1978-1999*
PE	0.01	0.11	0.25		0.06	0.22	0.06
PVC	0.21	0.25	0.3		0.01	0.33	0.12
Asbestos Cement	0.34	0.64	0.68		1.92		1.44
Steel	0.08	0.11	0.15				
Gray Cast Iron	1	1	1	1	1	1	1
Ductile Iron (no corrosion protection)				0.81	1.75		
Ductile Iron (corrosion protection)					0.22		0.12

Source: Eisenbeis, P., P. Le Gauffre, and S. Saegrov. Water Infrastructure Management: An Overview of European Models and Databases, AWWARF Infrastructure Conference and Exhibition Proceedings, Baltimore, Maryland, 2000.

* Relative failure rate = (Failure rate of the material concerned / Failure rate of Cast Gray Iron) for Reggio-Emilia and NTNU-SINTEF; and relative failure rate =[h (ductile iron)] / [h(gray cast iron)], with h the hazard function calculated with Failnet model. If the value is more than 1, the material will break more than the GCI.

Influence of Pipe Diameter on Pipe Failure Rates

European researchers have found that pipe diameter significantly influences pipe failure rates. Specifically, the failure rates for a particular pipe material increase as pipe diameter decreases. Researchers found (Table 2-9) that the relative failure rate for different pipe diameters can be quite different based on the data collected from one model to another and from one municipality to another, but that the same trend appears with the exception of the NTNU/SINTEF study. Researchers there noted that other location and maintenance factors may have contributed to the low relative failure values. The researchers also qualified their conclusions by noting that the different model databases define and use the data element 'pipe diameter' differently. For example, the Failnet model considers the diameter as a quantitative variable, whereas AssetMap considers it as a qualitative variable by grouping diameters into ranges.

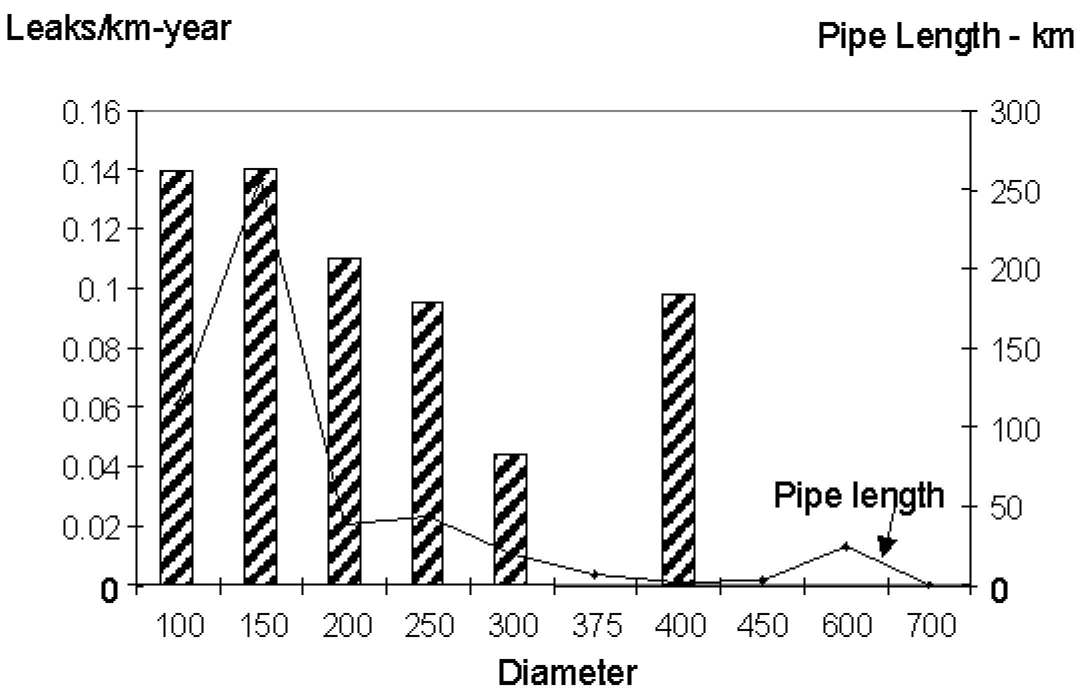
Other research supports this conclusion that failure rates are greater for smaller diameter pipes. A study on leak rates for water distribution pipes in Malmo, Sweden, also showed that leak frequency per kilometer of pipe decreased as pipe diameter increased (Figure 2-7).

Table 2-9. Sample relative failure rates* based on diameter of pipes used in water distribution systems

Failnet			AssetMap	NTNU/SINTEF		
Bordeaux (GCI, 1st fail.)	Charente M. (GCI, 1st fail.)	Sub. Paris (GCI, 1st fail.)	Lyon (GCI)	Trondheim	Oslo	Bergen
2.5	2.08	1.37	2.94	0.99	0.80	0.14

Source: Eisenbeis, P., P. Le Gauffre, and S. Saegrov. Water Infrastructure Management: An Overview of European Models and Databases, AWWARF Infrastructure Conference and Exhibition Proceedings, Baltimore, Maryland, 2000.

* relative failure rate for AssetMap is = [(average failure rate for pipe diameter A x (60-80 mm))]/[(average failure rate for group of pipes with diameter B x (150-175 mm))]; relative failure rate for Failnet model is = [*h*(60 mm)]/[*h*(150mm)], where *h* is the hazard function calculated by the Failnet model; relative failure rate for the NTNU/SINTEF model is = [average fail rate for group of pipes with diameter A (A <100)] / [average fail rate for group of pipes with diameter B (100<B<250)]



Source: Sundahl, Ann Christin. Diagnosis of Water Pipe Conditions, Lund University, Department of Water Resources Engineering, Lund, Sweden, 1996, ISSN 1101-9824.

Figure 2-7. Leak frequency for different diameter pipes in Malmo, Sweden (average leak frequency 1989 to 1994).

The results of a study[25] of the performance of sewer pipes in Trondheim, Norway, are shown in Figures 2-8 to 2-10. Figures 2-8 and 2-9 present trends for concrete sewer pipe collapses in Trondheim, relative to pipe diameter. As can be seen in Figure 2-8, the majority of the failures have occurred for pipes with a diameter less than 400 mm. Figures 2-9 and 2-10 show blockage statistics for groups of sewers, i.e., the two common pipe materials concrete and PVC. The results show that the small diameter pipes have a higher failure rate than the larger ones. Also, small diameter concrete pipes have a higher failure rate than similar diameter PVC pipes. Researchers concluded that this might be explained by the fact that the PVC pipes were constructed within the last decade, while many of the concrete pipes were much older.

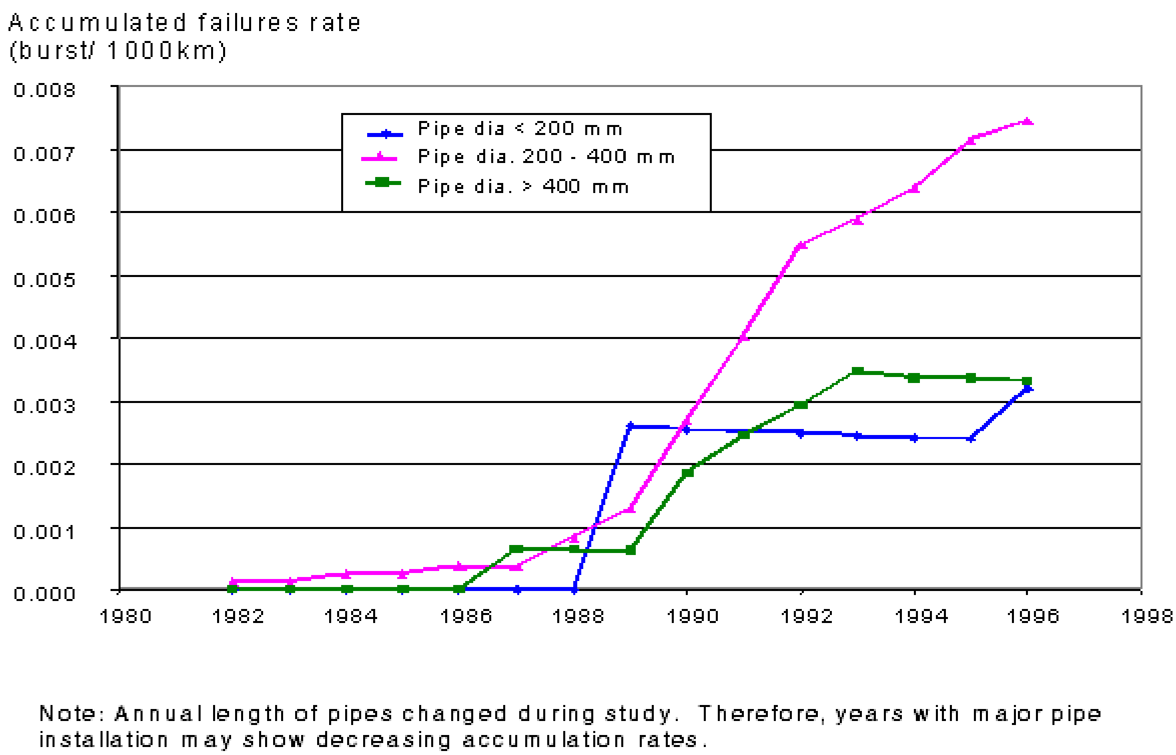
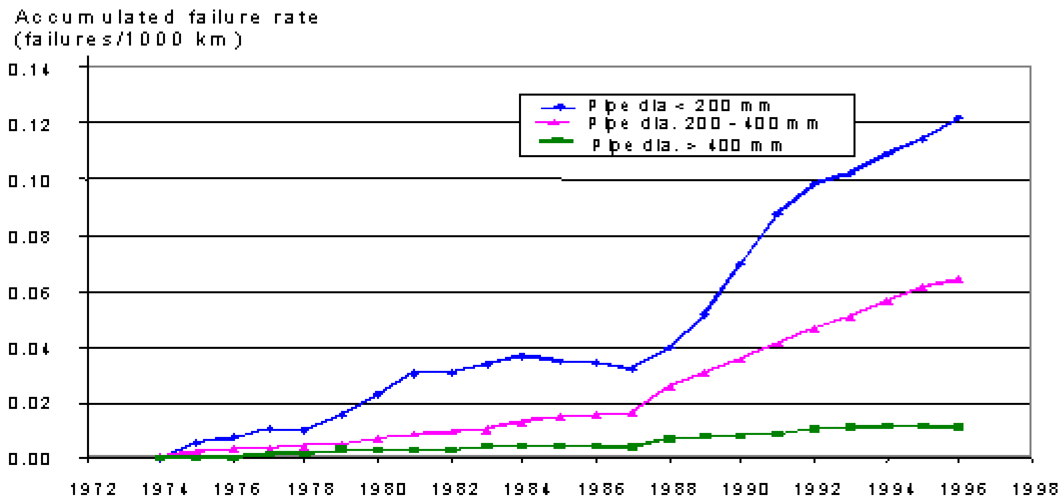


Figure 2-8. Collapses of concrete sewer pipes versus classes of pipe diameter in Trondheim, Norway.[26]

[25] Saegrov, S., Selseth, I., and Schilling W., Management of Sewer System Data in Norway. EWPCA Symposium, "Sewerage Systems – Costs and Sustainable Solutions." 4-6 May, 1999 in conjunction with 12th IFAT 1999 Exhibition, Munich, Germany.

[26] Ibid



Note: Annual length of pipes changed during study. Therefore, years with major pipe installation may show decreasing accumulation rates.

Figure 2-9. Concrete sewer blockages versus pipe diameter in Trondheim, Norway.[27]

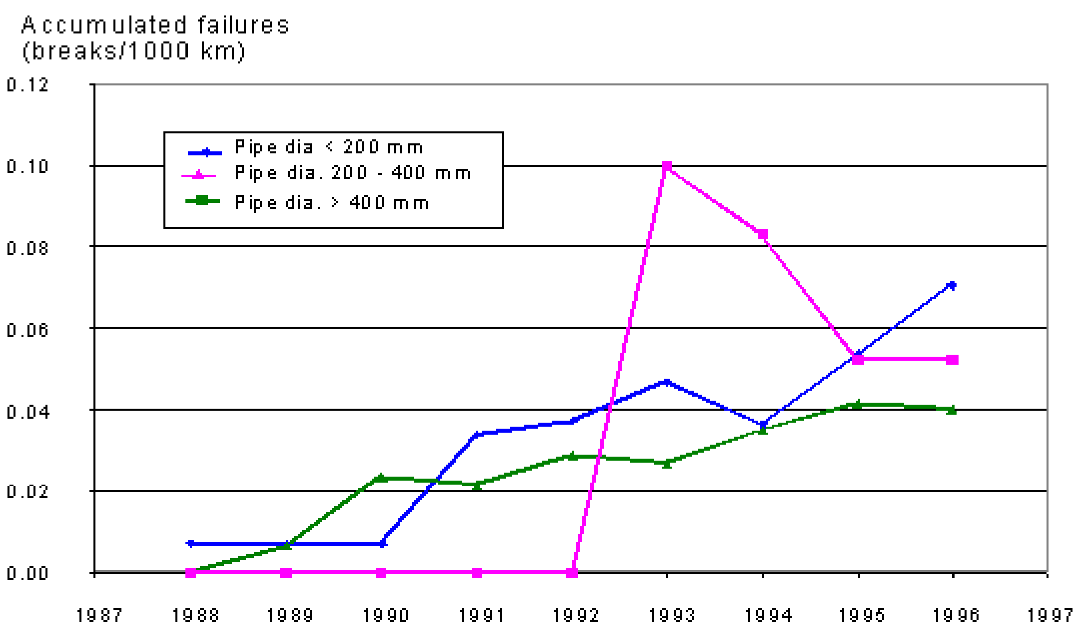


Figure 2-10. PVC sewer blockages for different diameters in Trondheim, Norway**.**

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[27] Ibid

Influence of Soil Conditions on Pipe Failure Rates

European researchers have found that as for diameter, the surrounding soil conditions significantly affect pipe failure rates. Table 2-10 presents relative failure rates for corrosive, alluvial, and clay soil characteristics. The low relative failure rate for alluvial soils, as determined from the AssetMap data, is noteworthy. This value contradicts the common assumption that alluvial soils result in increased pipe failures. In this case, some factors correlated with the pipes located in alluvial soils are creating an opposite effect.

Table 2-10. Sample relative failure rates for pipes in water distribution systems based on surrounding soil conditions

Failnet			AssetMap	NTNU/SINTEF
Relative Failure Rate = [h(corrosive soil)] / [h(non-corrosive soil)]			*Relative Failure Rate = [BR*(alluvium)³] / [BR(other)]*	*Relative Failure Rate = [h(clay)] / [h(non-clay)]*
Bordeaux (GCI, 1st fail.)	Charente M. (GCI, 1st fail.)	Suburb of Paris (GCI, 1st fail.)	Lyon (GCI)	Trondheim
1.75	3.64	1.33	0.72	3.09

Source: Eisenbeis, P., P. Le Gauffre, and S. Saegrov. Water Infrastructure Management: An Overview of European Models and Databases, AWWARF Infrastructure Conference and Exhibition Proceedings, Baltimore, Maryland, 2000.
* BR = average break or failure rate for each group of pipes.

Researchers also attributed the difference in the relative risk values to the fact that in each model, the definition of soil is different. In Trondheim, using the model NTNU-SINTEF, a rough classification has been applied to represent the "soil:"

- Very aggressive: (Tidal zone, high ground water level, natural soil with resistivity under 750 Ohm cm, pH less than 5, polluted by chemicals, stray current, etc.)
- Moderate aggressive: (Clay, wetland, nonhomogeneous, etc.)
- Not aggressive: (Natural soil resistivity over 2500 Ohm cm, dry conditions, sand, moraine).

In Lyon, researchers scanned geological maps (scale 1/50 000) to develop information about the soil type. In addition, areas with a history of soil movements (geotechnical risks) were defined in a previous study. This variable appears highly significant in explaining problems with joints and leak frequency. In Bordeaux, the soil type was defined from a specific study that sampled the resistivity of the soil in half of the covered infrastructure area. In a suburb of Paris and in Charente-Maritime, information about the soil was entered based on staff knowledge of soil corrosiveness.

Influence of Traffic and Loading Conditions on Pipe Failure Rates

European research has also shown that traffic load is a significant factor affecting pipe failure rates. Table 2-11 presents sample relative failure rates for high versus low traffic rates as recorded in the studies applying the Failnet approach. In the Failnet approach, traffic is taken into account as a qualitative variable according to the number of vehicles per hour or the type of road. As shown in the table, failure rates increase with traffic load in all three systems.

Table 2-11. Sample relative failure rates for pipes in water distribution systems based on traffic loads from Failnet

Relative Failure Rate = [h(high traffic)] / [h(low traffic)]	Bordeaux (GCI, 1st fail.)	Charente M. (GCI, 1st fail.)	Suburb of Paris (GCI, 1st fail.)
	2.30	3.00	1.77

Source: Eisenbeis, P., P. Le Gauffre, and S. Saegrov. Water Infrastructure Management: An Overview of European Models and Databases, AWWARF Infrastructure Conference and Exhibition Proceedings, Baltimore, Maryland, 2000.

For AssetMap and the case of Lyon, researchers developed six types of traffic conditions. These results display low differences between light and heavy or very heavy traffic, and can be considered a conservative estimate of relative risks. Studies[28] have shown that the location of pipes must be considered as uncertain data. In studying this uncertainty on a sample (a 211 km networks in Villeurbanne) with a Bayesian approach, the point estimate of the relative risk increased from 1.6 to 4 (see Tables 2-12 and 2-13).

Table 2-12. Sample relative failure rates for pipes in water distribution systems based on traffic loads from AssetMap model

(Traffic) x (Pipe Location) Case of Lyon	Point Estimate of Relative Failure Rate = BR* (Ei) / BR* (E0) and 95% confidence interval
E0: pipe under pavement	1
E1: under roadway with light traffic (<25 trucks/day)	1.13 ; [0.98 ; 1.30]
E2: under roadway with heavy traffic (25 - 300 trucks/day) E4: under secondary road	1.35 ; [1.18 ; 1.56]
E3: under roadway with very heavy traffic (>300 trucks/day) E5: under main (national) road	1.80 ; [1.37 ; 2.35]

Source: Eisenbeis, P., P. Le Gauffre, and S. Saegrov. Water Infrastructure Management: An Overview of European Models and Databases, AWWARF Infrastructure Conference and Exhibition Proceedings, Baltimore, Maryland, 2000.
* BR = average break or failure rate for each group of pipes.

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[28] Malandain J., Le Gauffre P., Miramond M. Organizing A Decision Support System For Infrastructure Maintenance: Application To Water Supply Systems, Proceedings. First International Conference on New Information Technologies for Decision-making in Civil Engineering. Montreal (Canada) 11-13 Oct. 1998, pp. 1013-1024. ISBN 2-921145-14-6

Table 2-13. Sample relative failure rates based on traffic loads from AssetMap model

Pipe Location	Point estimate of relative failure rate and 95% confidence interval, without considering uncertainty of data	Point estimate of relative failure rate and 95% confidence interval, considering uncertainty of data (Bayesian approach)
L0: pipe under pavement	1	1
L1: pipe under roadway	1.64 ; [1.06 ; 2.54]	4 ; [2.68 ; 5.96]

Source: Eisenbeis, P., P. Le Gauffre, and S. Saegrov. Water Infrastructure Management: An Overview of European Models and Databases, AWWARF Infrastructure Conference and Exhibition Proceedings, Baltimore, Maryland, 2000.

Influence of Initial Pipe Condition and Previous Breaks on Pipe Failure Rates

Research[29] in the US has shown that generally, each time a pipe is repaired, the time to the next repair is increasingly shorter. Although a few European studies discuss this phenomenon, we found little empirical data to support the hypothesis. One related study[30] was conducted on the sewers in Malmo, Sweden. Swedish researchers conducted TV inspections at least five years apart on 40 segments of pipes. Most of the pipes were old and had small dimensions. On initial inspection, researchers developed a score for the observed defects and assigned the pipes to one of three condition categories: good, medium, and poor. During the second inspection, researchers developed a new damage score based on observed defects.

To express the rate of structural decay, the researchers compared the damage scores between the two events and created the following three categories of decay rates:

SD 0 = no change in damage score
SD 1 = a small (undefined) change in damage score
SD 2 = a large (undefined) change in damage score

The result of this analysis is summarized in Figure 2-11. As can be seen, the rate of deterioration was greater for pipes in the poor initial condition.

European Experience Using GIS to Conduct Spatial Analysis of Pipe Failure Rates

Geographic Information Systems (GIS) are computer technologies that combine mapping and technical information to generate maps and reports. They provide an effective framework to collect, store, and use location-based information to improve planning and decision making. They can also create links among geographical data (e.g., network drawings), relational databases (e.g., database of network characteristics such as diameter, age, material, condition, etc.), and modeling tools

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[29] Clark, R.M., and J.A. Goodrich, Developing a Data Base on Infrastructure Needs. Journal of the American Water Works Association (AWWA). Vol. 81, No. 7. (1989) pp. 81 – 87.

[30] Lidström, V. "Investigation of Sewer Condition," Urban Underground Water and Waste-Water Infrastructure: Identifying Needs and Problems, Cost Action C3 Workshop, 18-19 June 1996, pp. 101-107.

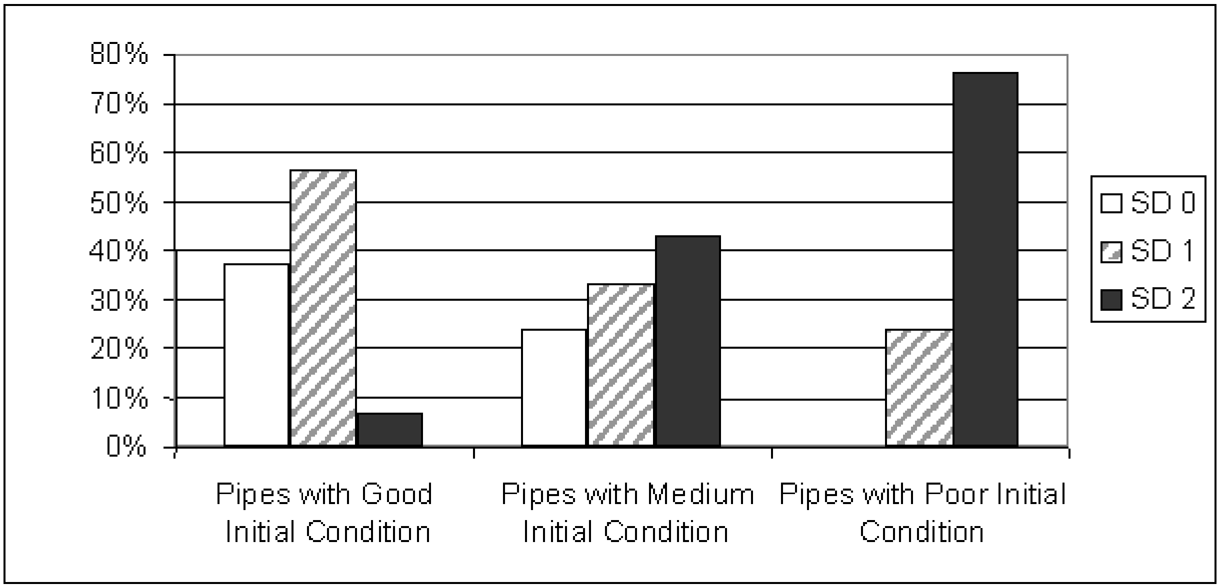

Figure 2-11. Relationship between rate of structural decay and initial condition of pipe, Malmo, Sweden[31]

(e.g., probabilistic tools that estimate chances of particular pipes failing based on pipe characteristics). The ability to integrate this disparate information makes GIS tools particularly useful for infrastructure asset management and rehabilitation planning.

Similar to US studies, Swedish[32] and English[33] GIS-based studies have found that leaks tend to occur in clusters rather than being evenly distributed throughout the network. For example, researchers in Sweden used a GIS system to display the annual average leak frequency (based on all leaks recorded from 1985 to 1994) in a subdivision of the city of Malmo. Figure 2-12 demonstrates how the spatial analysis of the leak frequencies can be used to identify subdivisions that experience extremely high leak rates. This fact can assist infrastructure managers in prioritizing rehabilitation plans.

However, it is important to note that GIS systems are resource-intensive, both in terms of cost (expensive), and in terms of data management (require large volumes of high-quality

[31] Lidström, V. *Diagnos Av Avloppsledningars Kondition (The Diagnosis of the Condition of Sewer Pipelines)* , Rapport 3194, Institutionen för Teknisk Vattenresurslära, Lunds Tekniska Högskola, Lunds Universitet, Lund, 1996.

[32] Sundahl, Ann Christin. Diagnosis of Water Pipe Conditions, Lund University, Department of Water Resources Engineering, Lund, Sweden, 1996, ISSN 1101-9824.

[33] Newport, R. 1981. Factors Influencing the Occurrence of Bursts in Iron Water Mains. Journal of AQUA No. 3, 1981, pp. 274–278.

data). Hardware typically includes workstations, plotters/printers, GIS software, and computer network servers with extensive storage space. Software typically consists of a computer-aided design system (e.g., AutoCAD™), a database application (e.g., Microsoft® Access™), and a GIS interfacing program (e.g., ArcInfo™) to marry the graphical data stored as maps with the data stored in relational databases. These applications are usually available in both high-powered versions for mainframe, or as lower-powered versions for desktop computers. No studies were found that compare costs and benefits of using a GIS.

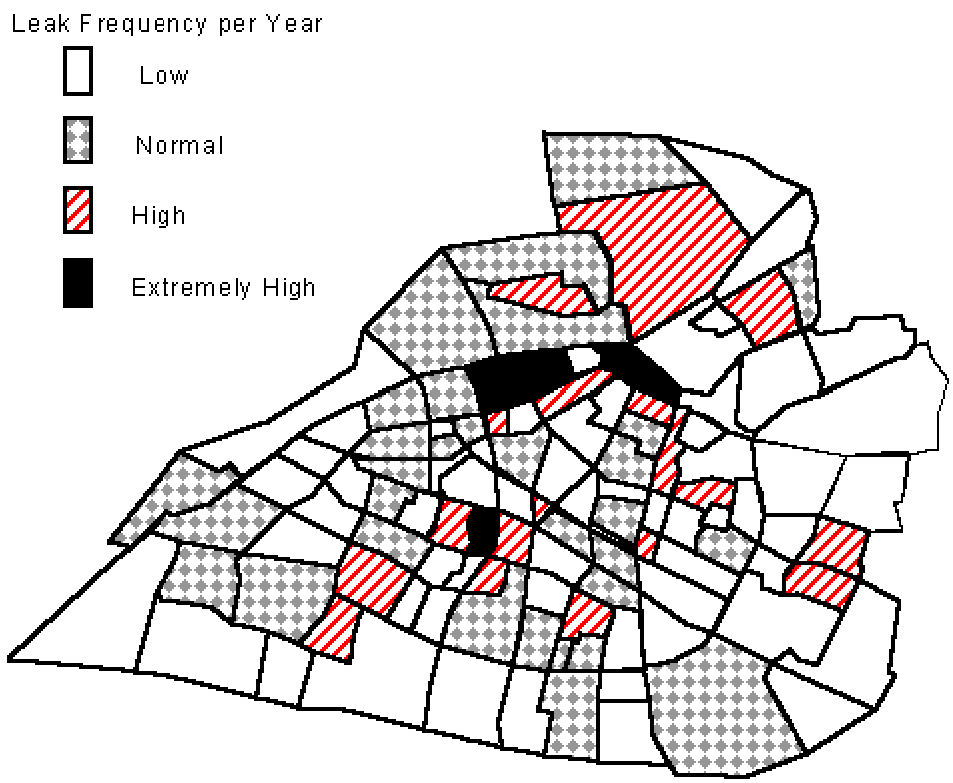

Figure 2-12. Spatial analysis of leak frequency for the subdivisions of Malmo, Sweden

From a data management perspective, GIS consists of three major elements: data entry, data manipulation, and data output. Graphical data, as well as location-specific data, must be entered into the GIS. When a utility moves to GIS (as many have), they must manually enter much of the required data. Data manipulation consists of evaluating and modeling the data entered into the GIS, allowing the water utility to evaluate spatial data and alternatives. Finally, the data output element graphically displays the results of the data manipulation element. Data output can be printed or plotted and is usually in the form of maps, tables, and digital files.

Summary of European Models to Assess Pipe Condition and Support Proactive Rehabilitation Planning

Through a review of European research papers, company product literature, and interviews with European researchers and practitioners, eight models or methodologies that are designed to support rehabilitation planning were identified. To provide an overview of each of the European models discussed in this paper, its capabilities to quantify and rank the condition of a pipeline from factors such as structural deterioration (e.g., failure rate), hydraulic capacity, water quality, and economics are described. Table 2-14 provides a summary of the capabilities of each model.

It is important to note that the summary of system capabilities was based solely on a review of documentation and previous studies and not on independent validation or verification of the software function. Neither USEPA nor LMI makes any endorsement of the products discussed.

Conclusions

Based on the review and analysis of European research and product literature related to the use of models for rehabilitation management, it was found that:

- There is still not a widespread use of modeling applications[34] in Europe. Each model presented in this paper has been applied in select urban or rural water services, but not on a large national scale. UtilNets is the most comprehensive model. It contains capabilities to model pipe failures, water quality, and rehabilitation scenarios. However, it is only in the prototype development stage.

- Although the studies reviewed pointed to the high cost of data collection in Europe, no studies were found to compare the collection costs to the benefits received. However, some did give an indication of the magnitude of costs. For example, the East of Scotland Water Service estimated that the cost of data capture was about 80% of the total cost of its GIS and rehabilitation management system prior to rolling it out to operational staff. Because data collection costs are high, water services must avoid the unnecessary collection of data that will rarely, if ever, be used, e.g., the number of step irons in a manhole. Therefore, managers must ensure that the data they collect has a business requirement. One approach to minimizing data collection costs is to collect only the minimum data elements (pipe material,

[34] Eisenbeis, P., P. Le Gauffre, and S. Saegrov, Water Infrastructure Management: An Overview of European Models and Databases, AWWARF Infrastructure Conference, Baltimore, MD, 2000.

Table 2-14. Summary of capabilities of European water and wastewater infrastructure rehabilitation software applications/models

Model Name	Assets		Approach to Assess Current Network Conditions						Approach to Predict Future Network Conditions						User Interface/ Output	
	Water Distribution	Wastewater Collection	Observed Defects	Failure/Break/Burst Rate Analysis	Hydraulic Capacity/ Vulnerability Analysis	Current Asset Value, O&M, and Estimation	Water Quality Modeling (Water Only)	Prioritization System to Select Critical Pipes for Rehabilitation	Predicts Failure Rates/Replacement Dates	Predicts Hydraulic Capacity or Vulnerability	Predicts Future Asset Value	Predicts Future O&M and Rehabilitation Costs	Predicts Changes to Distributed Water Quality (Water Only)	Compares Future Network Rehabilitation Scenarios	GIS	Report Generator
AQUA-WertMin 4.0	X	X	X	X		X		X	X	X	X	X		X		X
AssetMap	X		X	X		X		X	X					X	X	X
EPAREL/ EPANET	X		X	X			X	X	X	X			X			X
Failnet	X		X	X	X	X			X	X	X	X		X		X
Gemini VA	X	X	X	X	X	X		X	X	X				X	X	X
KANEW	X		X	X	X	X		X	X	X	X	X		X		X
KureCad	X	X	X	X	X	X		X		X	X	X			X	X
UtilNets (prototype)	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X

age, section length, number of breaks or bursts, and diameter) required by the models to develop a prioritized list of pipes (as shown in Table 2-4). Water authorities can then use this prioritized list of pipes to direct the collection of the additional data elements listed in Table 2-4. Also, managers can modify maintenance worksheets to enable site crews to capture the appropriate data as part of their routine site repair operations.

- Spatial analysis plays an important role in rehabilitation planning since the research shows that a significant number of failures appear in geographic clusters. However, only four of the models (AssetMap, Gemini VA, KureCad, and UtilNets) integrated a GIS user interface. All of the models had the capability to produce reports and graphics for comparison and trending purposes.

- The concept of modeling the impact of pipe failures on water quality and using that information for rehabilitation planning has not yet been implemented in practice. Only the EPAREL/EPANET and UtilNets models integrated a water quality module and they are still in the development stage.

- High quality, consistent data is essential for developing accurate models. Water and wastewater infrastructure operations and maintenance decisions must be based on analysis of reliable data that reflects the true status of a pipe system. It is evident from the European research that if a model or application is to gain the support of the engineering staff who use the records on a daily basis, the data used by the application or model must be accurate. At a minimum, the quality of the data should be flagged to warn the user of possible inaccuracies. European researchers note that even if water services in a region do use the same model, existing data collection methods vary considerably from service to service since the data entered into the models has typically been inherited from historic paper-based record-keeping approaches.

- Finally, European researchers note that sharing data across water services would reduce costs of data collection and improve modelling accuracy.

Chapter 3
Summary of European Performance Indicators for Water Distribution and Wastewater Collection Infrastructure

The historical performances of water distribution, sewer collection pipes, or networks have been used as indirect estimations of pipe or network conditions and rehabilitation needs. Examples of such performance indicators (PIs) are the number of distribution pipe bursts, distribution system leakage, sewer collapses, and sewer blockages. In Europe, three initiatives were found that use performance indicators for asset management and recapitalization purposes: the Italian Reggio water distribution system, the Scandinavian Six-Cities Group performance benchmarking consortium, and the United Kingdom's (UK's) Office of Water (OFWAT) annual and five-year system serviceability assessments. Each case description includes the PIs used, the types of decisions made, and provides a summary list of the indicators.

Although the intent was to also provide a cost-benefit evaluation regarding the use of indicators, data collection cost or benefit information was unable to be identified.

Background on the Use of Performance Indicators for O&M and Rehabilitation Planning

How is the effectiveness of water and wastewater infrastructure measured? The answer to this question is not easy to come by, but is an essential one if a meaningful framework for assessing its performance can be created. A National Research Council (NRC) study[35] on measuring and improving infrastructure stated that:

> *"...performance was the degree to which infrastructure provides the services that the community expects of that infrastructure [and] can be defined as a function of effectiveness, reliability and cost...."*

This general concept of using performance measures as a management tool is straightforward: you can't improve the performance of a system unless you measure it. However, the NRC implies that there is no single definition of good performance. Rather, good performance is determined by meeting the expectations of the community stakeholders. Therefore, understanding the expectations of community stakeholders is essential if infrastructure managers are to clearly demonstrate how a particular infrastructure system is performing against indicators of effectiveness, reliability, and costs.

Since there are no standards for infrastructure performance, infrastructure managers and community

[35] National Research Council, Committee on Measuring and Improving Infrastructure Performance, Measuring and Improving Infrastructure Performance, National Academy Press, Washington D.C., 1995. ISBN 0-309-050987

stakeholders have found it difficult to identify performance targets, establish meaningful indicators of performance, and use the information to make decisions or communicate results to the public. However, there are general guidelines[36] that can assist infrastructure managers and community stakeholders with their efforts. Managers should look to select indicators of effectiveness, reliability and cost that enable them to:

- Compare what the water authority did related to O&M, rehabilitation, and new construction with what they planned to do. For example, this can be demonstrated by listing the planned rehabilitation activities in relation to the annual accomplishments.

- Compare the infrastructure network's present performance with past performance to observe the trends of key performance indicators. Is it more effective, reliable, and less costly to maintain than before? The number of pipe breaks is one of the most commonly used indicators of effectiveness, but to be meaningful, managers should assess its trend over time to determine if O&M and rehabilitation policies are having a positive impact on system costs, water quality, or meeting customer expectations.

- Compare the water authority's performance to other similar water authorities. This "benchmarking" approach is an important internal tool for monitoring best practices, and ensuring that the water authority is keeping up with best internal and external practices. Although trend analysis of performance metrics is an important exercise for a water authority to undertake individually, it can provide more useful information if the results are compared across many water authorities by a third-party organization or government agency.

- Compare the water authority's processes and performance to existing protocols - of which there are many. In addition to the water authority's internal standards, such as maintenance procedures and repair goals, there are a variety of industry recommendations and a host of criteria offered by a wide range of organizations such as the American Water Works Association, the American Society of Civil Engineers, and many others.

Whichever framework is used to measure the water authority's performance in operating, maintaining, and rehabilitating its infrastructure, both management and external watchdogs should look to performance benchmarking as a method to achieve the community's expectation for effectiveness and reliability at the lowest possible life-cycle costs.

European Case Studies

In reviewing the European experience, focus was put on case studies where managers used performance indicators as they relate solely to the management and rehabilitation of water

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[36] Friend, Gil, Evaluating Corporate Environmental Performance, The New Bottom Line, Issue 5.22, Berkeley, CA, October 21,1996.

distribution and wastewater collection pipe networks. It is important to note that these performance indicators are usually developed as part of a comprehensive performance assessment program aimed at improving operations across a water or wastewater authority. In addition, examples are provided on how performance indicators can be used by one water authority, a regional consortium of water authorities, and by a federal government.

Italy Reggio Water Distribution Network

One of the simplest uses of performance indicators to improve operations comes from a case study[37] of the water distribution network in Reggio, Italy. It involves the use of performance indicators by AGAC, a private water authority, to reduce leakage rates. AGAC management believed that the distribution system was experiencing excessive leakage rates and implemented a performance improvement program to reduce the amount of water lost. Since the target audience for this effort was the system operators or management, the indicators selected focused strictly on reducing the system leakage, both in terms of total amounts and as a percentage of total water produced. To calculate the values for the selected indicators, AGAC had to measure the water produced and the water delivered to the consumer, in total and for each district of the network. Table 3-1 lists the performance indicators and required data for the Reggio case study.

Table 3-1. Summary of performance indicators and required data for Reggio Water System, Italy, 1994 Leakage Study

Performance Indicator		Required Data	
Definition	Unit	Definition	Unit
Total amount of leakage = total water produced minus the total water demand from billing data (total and by district)	Cubic meter	Water produced – total annual (total and by district)	Cubic meter
Percentage of leakage = total leakage divided by total produced (total and by district)	%	Water billed – total from billing data (total and by district)	Cubic meter

To collect the necessary data, AGAC divided the network into districts that were served by one or two water mains and installed flow meters on those pipes. With the meters in place, AGAC collected data on the volume of water flowing to a district, and collected billing data from consumer meter readings. To calculate the leakage amount for the system, AGAC compared flow measurements into each district with the consumer meter readings for each district. Through the analysis of this data by district, AGAC was able to identify districts with high leakage or faulty point-of-use meters. Those districts with high leakage rates were then given priority for detailed pipe evaluations, through which operators identified specific leaking pipes. This effort resulted in an overall annual reduction of water losses of 52% in 1994, as compared to 1989. Table 3-2 shows the performance of the leak monitoring system by comparing the water loss data for 1989 to 1994 for the Reggio water system. AGAC realized an additional benefit from installing district meters: it

[37] Schiatti, Marcello, Ing., "Active Control of an Urban Distribution Network", Urban Underground Water and Waste-Water Infrastructure: Identifying Needs and Problems, Cost Action C3 Workshop, 18-19 June 1996, pp. 109-117.

created a long-term flow monitoring system that enabled it to continuously monitor leakage rates.

Table 3-2. Leakage data for Reggio E. Water System, Italy (1989 versus 1994)

Year	Water Produced (cubic meter)	Water Billed (from billing meters) (cubic meter)	Leakage (produced - consumed) (cubic meter)	Percentage Lost
1989	16,153,000	9,486,000	6,667,000	41%
1994	14,079,000	10,857,000	3,222,000	23%
5-year reduction water lost				52%

This case study is an example of a simple use of PIs in that it only involved an intra-system comparison of a very specific indicator of network effectiveness (leakage). AGAC used the trend in performance over time to judge success. In this case, success was a reduction in leakage rates from 1989 to 1994.

Scandinavia Six-Cities Group

Another example[38] of the use of performance indicators comes from the Six-Cities Group, a consortium of water authorities from four Scandinavian countries. This case study involves a group of six water authorities joining together in a private consortium to identify and use performance indicators as a mechanism to improve operations among members.

The six cities are Copenhagen in Denmark, Oslo in Norway, Helsinki in Finland, and Stockholm, Gothenburg, and Malmo in Sweden.

At the inception of the Six-Cities Group, the utilities were owned by the cities. In the 1990s, discussion arose regarding the privatization of the water authorities. At this meeting, the utility managers found that they could not demonstrate that their utilities performed well. As a result, the managers decided to form a consortium, the Six-Cities Group, to share information and to develop indicators of performance. They selected seven business areas in which to measure performance:

- Business-wide management,
- Production of drinking water,
- Distribution of drinking water,
- Collection of wastewater and stormwater,

[38] Helland, B., and J. Adamsson, Performance Benchmarking Among 6 Cities in Scandinavia. Oslo, Norway: Oslo Water and Sewage Works, unpublished white paper.

- Treatment of wastewater,
- System construction and rehabilitation, and
- Finances.

For each business area, they looked for indicators of customer satisfaction, cost-effectiveness, and environmental impact. Table 3-3 provides a description of the performance indicators for the business areas directly related to water distribution and wastewater collection.

The Six-Cities Group continues to develop and refine the performance indicators each year. Managers meet at the beginning of each year to refine the PI definitions and begin the data collection process. Each water authority completes the data collection form electronically and submits it to the consortium committee. At the end of each year, managers meet and present the results for their system in an agreed-upon format.

To date, the participants have found that despite the differences that exist among the cities (e.g., different languages and currencies) it is possible to compare the performance. However, managers noted that to do so, it is essential to clearly define the data collection requirements and the indicators.

Although the Six-Cities Group continues to refine its approach, this case study demonstrates how a voluntary association can adopt a wide variety of PIs for both intra-system and inter-system comparisons. Its approach has enabled participants to identify best-in-class practices during annual reviews and to identify trends for each participant as they continue to measure performance over a 5- to 10-year period.

United Kingdom's Office of Water (OFWAT) System Serviceability and Performance Assessments

One of the best and most developed examples[39] of PI usage comes from the UK. Since the privatization of water and wastewater systems in the UK, the Office of Water (OFWAT) has required the private companies to maintain their extensive infrastructure of water mains and sewers in a manner that provides "adequate" services to current and future customers. The goal is to ensure that private companies provide adequate investments in infrastructure while maintaining competitive rates. OFWAT reviews company performance annually and at each 5-year review of company price rates and request for license renewal.

For the 5-year license renewal performance assessment, OFWAT reviews each company's PIs for the previous 5 years, as well as its plans for the future O&M and rehabilitation of its infrastructure. Based on this review, OFWAT in effect approves each company's capital reinvestment budget.

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[39] Office of Water (OFWAT), Comparing Company Performance. OFWAT Information Note No. 5, London, England, July, 1995 (revised February 1998). This paper and additional information can be obtained from the OFWAT web site at http://www.open.gov.uk/ofwat/pubslist/pubsinfn.htm

Specifically, it approves a water company's request to set future prices at a level that will provide sufficient funds to maintain its network. Companies are required to carry out any work needed to

Table 3-3. Description of PIs related to water and sewer pipes for Swedish Six–Cities Group

PI Category	PI Description
Business-wide	Customer inquiries—under development
	Energy consumption per customer
	Energy production per customer
	Cost of chemicals per cubic meter of water produced
	Cost of chemicals per cubic meter of treated wastewater
	Number of employees per 1,000 customers
	Personnel cost per customer
	Percent of "In-house work" of total cost
	Cost per cubic meter of water sold (distributed on type of cost and activity)
	Cost per cubic meter of wastewater treated (distributed on type of cost and activity)
	Income (distributed on type of activity)
Distribution of drinking water	Interruptions (minute/customer)
	Number of breaks per 10 km of pipe length
	Leakage (l/min/km)
	Cost per cubic meter of water sold (distributed on type of cost)
	O&M cost per meter of pipe length
Collection of wastewater and stormwater	Number of blockages per 10 km of pipe length
	Number of flooding per 1,000 consumers
	O&M cost per meter of pipe length
System construction and rehabilitation	Reconstruction per renovation of water pipes (percent of total length)
	Rehabilitation (spending per cubic meter water sold)
	New construction (spending per cubic meter water sold)
	Rehabilitation of sewers (percent rehabilitated of total length)
	Rehabilitation of sewers (percent rehabilitated of total length)
Financial indicators	Under development

rectify deteriorating serviceability to customers, either before license transfers or as part of the new license, but at no cost to customers. The need for such work at a license transfer would be reflected in the company value at transfer. Such a potential liability should provide an incentive for the companies to ensure that they maintain the serviceability of the water main and sewer networks. OFWAT's 5-year assessment is based on the concept of serviceability to customers. It examines the overall trends for a range of PIs that describe the performance of the distribution and collection systems. By examining the trends over several years, OFWAT determines whether the O&M and rehabilitation carried out by the company has resulted in stable, improving, or deteriorating services to customers.

- If the assessment shows stable serviceability, then OFWAT's initial judgment would be that a continuation of past levels of O&M and rehabilitation activity should be sufficient for the next price limit period.

- If the assessment shows improving serviceability, then OFWAT's initial judgment would be that slightly lower levels of O&M and rehabilitation activity should be sufficient to deliver stable serviceability in the next price limit period.

- If the assessment shows deteriorating serviceability, then OFWAT's initial judgment would be that past levels of O&M and rehabilitation activity have not been adequate. OFWAT considers a decline in serviceability a serious shortfall in company performance.

OFWAT also conducts an annual review of company performance against various predefined PIs. Although OFWAT does not use this information to review pricing or licensing issues, it does publish a "Level of Service Report"[40] which compares company performance in delivering customer service and in providing water supplies and sewerage services. The report provides an intra-company assessment of performance trends, an inter-company comparison of performance and industry averages and an extra-company comparison to select benchmarks from other industries. These assessments provide information on the quality of individual services delivered to customers and allow OFWAT, the public, and the customers to judge how well the companies are performing.

DESCRIPTION OF PERFORMANCE INDICATORS[41]

The OFWAT assessment of company performance focuses on the delivery of services to customers. There are six key categories of PIs for assessing the water and wastewater companies:

- water supply,
- water distribution,
- sewerage service,
- customer service,
- environmental impact, and
- infrastructure costs.

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[40] Office of Water (OFWAT), 1998-99 Report on Levels of Service for the Water Industry for England and Wales, London, England, September 1999. This paper is available from the OFWAT web site at http://www.open.gov.uk/ofwat/pubslist/pubsinfn.htm

[41] Office of Water (OFWAT), Level of Service Indicators, OFWAT Information Note No. 40, London, England, March 1998. This paper is available from the OFWAT web site at http://www.open.gov.uk/ofwat/pubslist/pubsinfn.htm

In each of these areas, OFWAT has developed specific output PIs based on a number of considerations. These considerations are: services measured should be of real importance to customers and, where possible, based on those used in the published reports; PIs should be meaningful to companies and customers; PIs should be supported by high-quality data; and PIs that can be objectively assessed are preferred.

The specific PIs OFWAT has developed related to water and sewer networks are described further in the following paragraphs and summarized in Table 3-4.

Indicators of Customer Service

Data on current levels of customer service is available from two key sources — the companies and the customer service centers (CSCs). It exists in a number of forms, from the objective data provided annually by companies in the July return, and from the assessments of service made by the CSCs. Four objective and independently audited measures of customer contact are available and have been included in this overall assessment — response to billing contacts, replying to written complaints, issuing bills for metered customers (DG8), and speed of response to telephone contacts. Two of these metrics — response to billing contacts and replying to written complaints — have a long enough history to be used in the analysis of performance improvement. Customer service clearly goes wider than the speed of response to complaints and frequency of reading meters. The assessment is mostly based on objective facts about the service offered. The assessment of information to customers is currently based on information obtained through the billing process. Members of the CSCs and companies have expressed concern that there are currently no measures reflecting the quality of replies to complaints or the quality of the telephone service provided. With respect to written complaints, the limited results of CSC audits are being used to update the 1996 analysis of company complaint handling procedures.

Billing Contacts

This indicator shows the total number of written and telephone-billing contacts received by a company, and the number dealt with in 2, 5, 10, 20, and more than 20 working days. A billing contact is any inquiry (but not a complaint) about a bill - for example, an account query, change of address, or request for alternative payment arrangements. Complaints are covered by the metric associated with the company performance in replying to written complaints.

Replying to Written Complaints

This indicator shows the total number of written complaints received by a company, and the number dealt with in 2, 5, 10, 20, and more than 20 working days. A written complaint is any letter that draws attention to any service provided or action taken by a company (or its representatives) which falls short of the customer's expectations. Complaints that the company considers unjustified must still be included.

Table 3-4. Description of the UK OFWAT's performance indicators related to water distribution and wastewater collection systems

PI Category	Performance Indicator
Customer Service	Billing contacts
	Written complaints
	Bills for metered customers
	Ease of telephone contact
Water Distribution	Number of properties reporting low water pressure
	Water leakage in ml/day
	Km of mains relined
	Km of mains renewed
	Total km mains relined & renewed
	Number of burst mains per 1000 km
	Unplanned interruptions
Wastewater Collection	Number of pollution incidents at sewers
	Number of sewer collapses per 1000 km
	Number of properties affected by flooding (overloaded sewers), except due to the effects of extreme weather
	Km of sewers renovated
	Km of sewers replaced
	Total km of sewers renovated & replaced
	Total % of properties reporting internal sewage flooding
Infrastructure Costs	Water Infrastructure Main Installation Costs (average, maximum and minimum actual unit cost/unit length by type)
	Water Infrastructure Main Rehabilitation Costs (average, maximum and minimum actual unit cost/unit length by type)
	Sewerage Main Installation Costs (average, maximum and minimum actual unit cost/unit length by type)
	Sewerage Main Rehabilitation Costs (average, maximum and minimum actual unit cost/unit length by type)

Bills for Metered Customers

This indicator shows the percentage of metered customers who receive at least one bill during the year based on an actual meter reading. An actual meter reading is a reading taken by the water company, or one provided to the company by the customer (in response to an estimated bill, or as a result of a request for the information). Companies also report the number of meters that they have not read in two years or more.

Ease of Telephone Contact

This indicator identifies the ease with which customers can make telephone contact with their local water company, showing speed of response within 15 and 30 seconds, the number of abandoned calls, and the amount of time all lines to the company were engaged. Incoming telephone traffic on the main, advertised customer contact numbers (e.g., the customer service department, accounts section, or the main switchboard) is monitored.

Indicators of Water Distribution and Quality

Two important aspects of company performance in supplying water are pressure and interruptions to supply. OFWAT reviews performance in these areas annually against predefined standards for pressure and interruptions - the results are published in OFWAT's annual Level of Service Report. The PI related to inadequate pressure measures the total number of properties at risk of receiving water below a prescribed rate of flow and pressure. The data is derived from a company assessment of risk and allows exclusions for abnormal demand. Performance improvement is measured by the total number of pressure problems solved through company action since 1992 (this excludes properties added to or removed from the 'at risk' categories because of select information). The methodologies associated with company risk assessment are now generally sound, and the data is considered suitable for comparative purposes.

Companies provide data in their July returns to OFWAT on planned and unplanned interruptions to supply. The Level of Service report concentrates on the latter, and uses a scoring system to reflect the number and duration of interruptions in order to produce comparative performance assessments. These results have been used in this analysis. Planned interruptions have not been included because of the difficulty in accounting for the impact of different maintenance techniques used by the companies.

Performance improvement in the area of interruptions to supply is based on a comparison of the rolling average figure for interruptions in excess of 12 hours (the only data available with a history since 1992) for 1992–1995 and 1994–1997.

Inadequate Pressure

This indicator shows the number of residential properties which have received (and are likely to continue to receive) pressure below a certain reference level when demand for water is not abnormal. The reference level of service is defined as 10 meters head of pressure at the boundary stop tap, with a flow of 9 liters per minute. This should be sufficient to fill a 4.5-liter container in 30 seconds from a ground-floor kitchen tap. Because it is impractical to measure the pressure and flow at the boundary of every customer's property, companies are allowed to report against an alternative reference level, which is normally 15 meters head of pressure in the distribution main supplying the property. This is a sufficiently high pressure, even allowing for the connection from the water main to the property boundary. Companies are expected to keep registers that identify the properties at risk of receiving low pressure.

Supply Interruptions

This indicator shows the number of properties experiencing interruptions lasting longer than 6 hours, 12 hours, and 24 hours, which are the responsibility of the water company and are unplanned and without warning. Supply interruptions are excluded if a third party causes them. Companies also provide information on the number of supply interruptions that result from planned maintenance work and overrun the stated restoration time. Companies are required to keep registers that identify those properties affected by supply interruptions.

Restrictions on Use of Water

This indicator shows the percentage of a company's population that has experienced restrictions in using water. There are several categories:

- hosepipe (residential water use) restrictions,
- sprinkler/unattended hosepipe restrictions, and
- drought orders restricting non-essential use of water.

Companies are required to report the percentage of their population affected by any of the above water restrictions.

Indicators of Sewer Performance

OFWAT collects and publishes annual data on company performance for flooding due to inadequate sewer capacity (including an assessed risk of flooding, as well as actual incidents), and flooding incidents related to the condition of sewers and associated equipment. The former results from long-term problems that generally can only be resolved by capital investment; the latter are generally the result of insufficient, ongoing maintenance and are more within companies' control.

Combined sewer overflows are also part of the sewage collection system and, as such, might be expected to appear in this part of the assessment. However, OFWAT has included this PI in the environmental impact section, as failures will have their major effect on the receiving rivers and coastal waters.

Flooding from Sewers

There are two measures covered by this PI. First, this indicator shows the number of properties at risk of internal flooding from sewers due to overloading more than twice in 10 years and more than once in 10 years. Second, it lists the number of properties that are internally flooded due to either temporary problems, such as blockages or sewer collapses, or overloading.

Indicators of Environmental Impact

Customers are clearly interested in understanding the environmental impacts of the activities of companies, especially since these are a major driving force behind the increases in customers' bills. Therefore, OFWAT measures:

- Sewage treatment works failing their permit limits. Failures considered by the UK enforcement agency not to be reflective of company performance are excluded.

- Data on unsatisfactory combined sewer overflows. This reflects company progress in dealing with the problem of overflows that the UK enforcement agency considers unsatisfactory.

The annual total of major and significant incidents is expressed as a percentage of the resident equivalent population served by sewage treatment works to allow for the different size of companies. While OFWAT acknowledges that it may have been better to use the number of outlets where an incident could take place as a denominator, this data is not available.

Indicators of Infrastructure Costs

OFWAT uses the cost base method,[42] which it developed as part of its 1994 annual review, to determine the performance of the companies as it relates to installing new pipes or rehabilitating existing pipes. Company performance for each cost category is compared to the range of costs experienced by all companies for a particular cost component. OFWAT looks at the costs companies experienced to install new water mains and sewers, and to rehabilitate existing ones. Tables 3-5 to 3-8 present the definition of each PI and actual costs for water and sewer infrastructure in the UK for 1999.[43]

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[42] Office of Water (OFWAT), Infrastructure Renewals Accounting. OFWAT Information Note No. 36, London, England, February 1997. This paper is also available on the OFWAT web page at http://www.open.gov.uk/ofwat/pubslist/pubsinfn.htm

[43] Office of Water (OFWAT), Annual Report 1999 – 2000, House of Commons Paper 455, London, England, ISBN 0 10 556761 2, May 2000. This paper is also available on the OFWAT web page at http://www.open.gov.uk/ofwat/pubslist/pubsinfn.htm

Table 3-5. Water infrastructure standard costs in the UK – mains laying

Standard (std) cost	Description	Number of std costs submitted	Range of std costs submitted (£/meter)	Benchmark
General specification for mains laying: New water pipes laid in normal site conditions at a depth of no greater than 900 mm without any adverse complications. Pipe material is based on companies' own practices. Costs include all fixtures and fittings, ancillary works and reinstatement. Diameters relate to the nominal internal bore of the pipe.				
Grassland				
100 mm	Mains laid in urban/rural verges, new development sites or open field normally used for grazing. Excludes the cost of traffic management.	25	25 to 62	31
150 mm		25	28 to 76	37
200 mm		25	40 to 89	41
300 mm		24	60 to 130	65
450 mm		20	96 to 237	113
600 mm		17	141 to 342	176
Rural/suburban				
100 mm	Mains laid in secondary or minor roads and housing estates. Type 3 or 4 reinstatement and non-traffic sensitive in accordance with the New Roads and Street Works Act 1991.	25	62 to 118	71
150 mm		25	73 to 133	85
200 mm		25	83 to 149	95
300 mm		25	105 to 205	118
450 mm		18	159 to 344	232
600 mm		15	286 to 546	315
Urban				
100 mm	Mains laid in cities and town center trunk roads. Type 2 reinstatement and traffic sensitive in accordance with the New Roads and Street Works Act 1991.	21	73 to 160	81
150 mm		21	88 to 174	99
200 mm		23	101 to 195	112
300 mm		22	126 to 253	141
450 mm		16	191 to 367	236
600 mm		14	339 to 587	345

Table 3-6. Water infrastructure standard costs in the UK – mains rehabilitation

Standard (std) cost	Description	Number of std costs submitted	Range of std costs submitted (£/meter)	Benchmark
General specification for mains rehabilitation: Existing water pipes rehabilitated using particular techniques at a depth of no greater than 900 mm. All fixtures and fittings, ancillary works and reinstatement are included.				
Epoxy resin				
100 mm	Encrustation removed and pipe lined internally using an epoxy seal coat.	17	30 to 42	34
150 mm		17	29 to 45	38
200 mm		16	31 to 54	42
300 mm		12	31 to 73	46
Slip lining				
100 mm	Encrustation removed and a non-structural medium-density polyethylene pipe is inserted into the existing pipe.	4	37 to 63	44
150 mm		4	40 to 71	52
200 mm		4	46 to 96	62
Pipe insertion				
100 mm	Encrustation removed and a smaller structural pipe is inserted into the existing pipe.	6	28 to 59	50
150 mm		6	36 to 63	53
200 mm		6	55 to 77	67
300 mm		6	88 to 148	88
450 mm		7	117 to 180	135
600 mm		7	134 to 250	227
Pipe bursting				
100 mm	Encrustation removed and the existing pipe broken using an expander attached to a mole that compresses the resulting fragments of the existing pipe into the surrounding soil. As the pipe is broken, a new pipe is drawn behind the mole.	18	42 to 69	42
150 mm		18	51 to 97	51
200 mm		12	70 to 96	70

Table 3-7. Sewer infrastructure standard costs in the UK – sewer laying

Standard (std) cost	Description	Number of std costs submitted	Range of std costs submitted (£/meter)	Benchmark
General specification for sewer laying: New sewers laid assuming a depth of cover to the sewer is 2.0 meters to the crown of the pipe. Costs include a sewer junction and cap at 10 meter intervals and 50 meter intervals between manholes. Costs are based on open-trench pipe laying, with all other assumptions consistent with the relevant design and construction guidelines in Sewers for Adoption (4th Edition). Diameters relate to the nominal internal bore of the pipe.				
Grassland				
150 mm	Sewers laid in urban/rural verges, new development sites or open fields normally used for grazing. Excludes the cost of traffic management.	10	76 to 150	87
225 mm		10	108 to 166	114
300 mm		10	121 to 192	141
450 mm		9	154 to 240	181
600 mm		9	196 to 316	232
900 mm		9	268 to 502	346
Rural/suburban				
150 mm	Sewers laid in secondary or minor roads and housing estates. Type 3 or 4 reinstatement and non-traffic sensitive in accordance with the New Roads and Streets Works Act 1991.	10	132 to 250	179
225 mm		10	157 to 284	210
300 mm		10	186 to 326	241
450 mm		9	250 to 388	255
600 mm		9	318 to 521	348
900 mm		9	449 to 775	515
Urban				
150 mm	Sewers laid in cities and town center trunk roads. Type 2 reinstatement and traffic sensitive in accordance with the New Roads and Street Works Act 1991.	9	171 to 275	185
225 mm		9	201 to 313	217
300 mm		9	233 to 359	249
450 mm		9	290 to 427	310
600 mm		9	382 to 573	382
900 mm		9	533 to 851	556

Table 3-8. Sewer infrastructure standard costs in the UK – sewer rehabilitation

Standard (std) cost	Description	Number of std costs submitted	Range of std costs submitted (£/meter)	Benchmark
General specification for sewer rehabilitation: Existing sewers rehabilitated using particular techniques. All sewers rehabilitated at a depth of cover to sewer of 2.0 meters. Costs include a sewer junction and cap at 10 meter intervals. Costs assume that linings are installed in 100 meter lengths and that adequate water supply is available on site. Diameters relate to the nominal internal bore of the pipe.				
Pipe bursting				
225 mm	Existing sewer is broken out by an expander attached to a mole and a new pipeline is drawn in behind.	5	124 to 196	139
300 mm		4	163 to 255	163
450 mm		4	220 to 349	220
Insituform				
150 mm	A flexible lining is inserted into the sewer, via existing manholes, under pressure of water and then cured by circulating hot water.	8	99 to 161	99
225 mm		10	92 to 165	114
300 mm		10	108 to 183	127
450 mm		10	150 to 250	150
600 mm		9	189 to 398	204
Main entry				
900 mm	Gunite, Glass Reinforce Cement or Glass Reinforced Plastic installed inside the sewer in short or continuous lengths	4	203 to 564	409

APPROACHES TO COLLECT DATA AND EVALUATE PIs

OFWAT requires all companies to submit a standard data collection worksheet for the annual reporting and 5-year license reviews. They also work with all the companies and encourage them to improve the consistency and comparability of information. OFWAT reviews the companies' values for PIs and assigns them a combined performance score of 5 to 50 as described in Table 3-9.

OFWAT also differentiates between companies that achieve a high level of performance based on sound information, and those whose performance is based on less-reliable data. OFWAT assigns a confidence grade to the reliability and accuracy of information companies submit. These grades have two parts: a reliability band based on how the data was gathered and a number indicating its likely range of error.

Table 3-9. The UK's OFWAT scoring criteria for assessing company performance

Performance Indicator	Data Source	Description	Performance Range	Scoring Criteria
Water pressure 1996–97	Company data	Company assessment of properties at risk of receiving low pressure	From 5.5% properties at risk (worst) to zero at risk	Percentage at risk figure scored from 5 (poorest performance) to 50 (best)
Unplanned interruptions to water supply	Company data	Properties affected by unplanned interruption to supply greater than six hours	Performance scores (combination of 6,12, and 24 hour interruptions) from 2.77 (worst) to 0.14 (best)	Comparison of interruption scores as used in the OFWAT Levels of Service report. Interruption scores scored from 5 (poorest performance) to 50 (best)
Sewer flooding incidents due to overloaded sewers	Company data	Properties flooded internally by sewage as a result of an overloaded company sewer	Percentage of connected properties flooded from 0.01 (worst) to 0.001 (best)	Sewer flooding incidents due to hydraulic incapacity excluding extreme weather events. Percentage figure scored from 5 (poorest performance) to 50 (best)
Sewer flooding incidents with causes other than capacity	Company data	Properties flooded internally by sewage — caused by blockages, sewer collapses, equipment failure etc.	Percentage of connected properties flooded from 0.035 (worst) to 0.005 (best)	Sewer flooding incidents due to hydraulic incapacity excluding extreme weather events. Percentage figure divided into ten bands and scored from 5 (poorest performance) to 50 (best)
Properties at risk of sewer flooding	Company data	Properties at risk of internal flooding from sewers more than once in ten years	Percentage of connected properties at risk from 0.244 (worst) to 0.12 (best)	Sum of properties at risk of flooding more than once in ten and twice in ten years expressed as a per- cent. Percentage figure scored from 5 (poorest performance) to 50 (best)

SUMMARY OF ACTUAL PIS FOR THE UK'S WATER MAIN NETWORKS

OFWAT's 1998 assessment[44] of the entire UK water distribution system found that overall, the serviceability of underground networks is improving (see Figure 3-1). Based on that review of performance indicators, OFWAT determined that at an industry level, the companies' current levels of capital reinvestment should be sufficient to maintain serviceability to customers in the next price limit period.

OFWAT aggregated the information provided by the companies to create an industry picture of the water main and sewer networks, covering the inventory of asset stock, and its valuation, condition,and individual performance (see Tables 3-10 and 3-11).

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[44] Office of Water (OFWAT), 1998-99 Report on Levels of Service for the Water Industry for England and Wales, London, England, September 1999. This paper is available from the OFWAT web site at http://www.open.gov.uk/ofwat/pubslist/pubsinfn.htm

Table 3-10. Inventory of UK water main pipes by diameter (March 1998)

<=300 bore (km)	<=600 bore (km)	<=900 bore (km)	>900 bore (km)	Total Stock (km)
245000	51000	21000	8000	325000

Table 3-11. Condition assessment of water mains in the UK (March 1998)

	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5
Proportion	46%	31%	12%	6%	5%

Notes on Condition Grades for Water Mains:

Condition grade 1: No failures, fully complies with modern standards.
Condition grade 2: No significant failures (minimal impact on service performance), not quite consistent with modern standards.
Condition grade 3: Deterioration beginning to be reflected in service levels or increased operating costs.
Condition grade 4: Considerable corrosion affecting service performance, nearing end of useful life, frequent bursts.
Condition grade 5: Substantially derelict and source of service problems, no residual life.

Companies estimated that the gross replacement cost of all the potable water mains with modern equivalent assets (MEA) to be about £39 billion. Around 11% of the potable water mains were assessed as poor condition (condition grades 4 and 5), compared to 9% reported as poor condition in 1993. Many companies have attributed small changes in the reported proportion of water mains in poor condition over the last 5 years to improvements in their management information systems and reporting methods. Analyses of the companies' Business Plans confirm OFWAT's assessment that there is no evidence of a significant deterioration in the condition of the aggregate potable water main network stock.

SUMMARY OF ACTUAL PERFORMANCE METRICS FOR THE UK'S SEWER NETWORK

OFWAT's 1998 assessment[45] of the entire UK wastewater collection system found that overall, the serviceability of underground sewer networks is stable and, in some companies, is improving (see Figure 3-2). Based on that review of performance indicators, OFWAT determined that at an industry

[45] Office of Water (OFWAT), 1998-99 Report on Levels of Service for the Water Industry for England and Wales, London, England, September 1999. This paper is available from the OFWAT web site at http://www.open.gov.uk/ofwat/pubslist/pubsinfn.htm

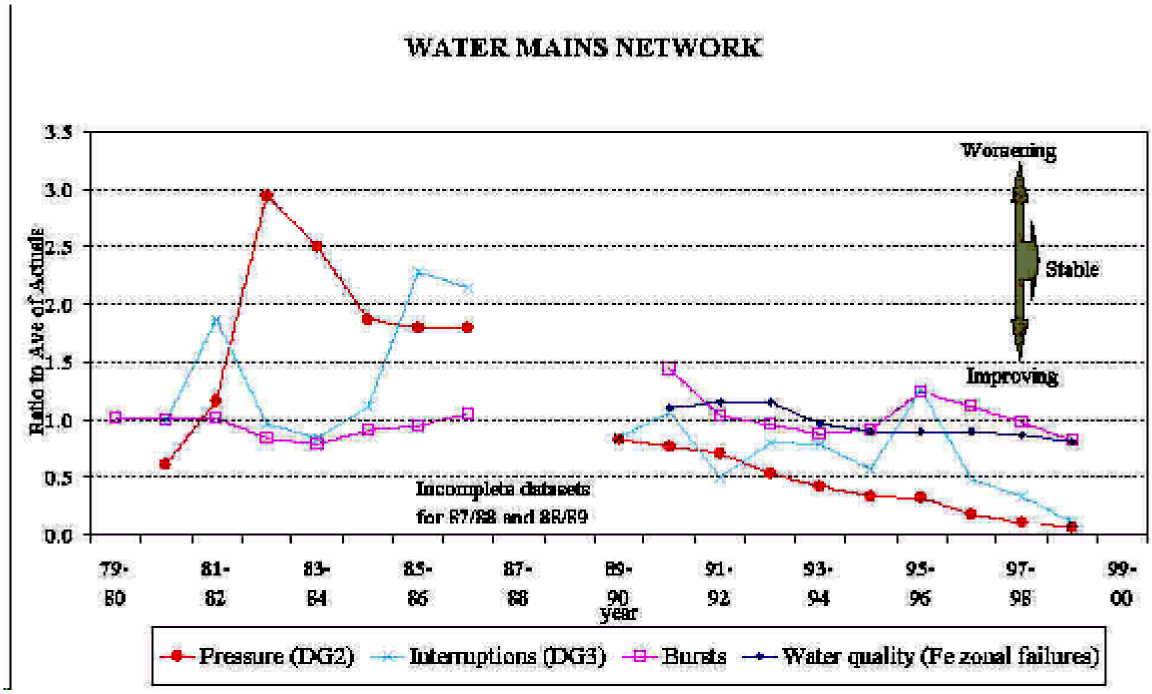

Figure 3-1. Summary analysis of trends of PIs for UK water mains for 1979-2000.[46]

level, the companies' current levels of capital reinvestment should be sufficient to maintain serviceability to customers in the next price limit period.

This approach, based on serviceability to customers, is a top-down method using a standardized approach to compare the detailed asset management plans of the individual water companies. OFWAT also recommends that companies' asset management plans link serviceability to customers with information on the performance and condition of the networks, so that work on the networks is effectively prioritized.

OFWAT sets price limits to enable sufficient maintenance of the water main and sewer networks such that a prudent and well-managed water company will be able to achieve stable serviceability. By accepting the price limit, the company commits itself to carrying out sufficient maintenance to achieve stable or improving serviceability. In August 1998, each company was required to assess its asset stock as of March 1998 in the Asset Inventory and System

[46] Office of Water (OFWAT), Annual Report 1999 – 2000, House of Commons Paper 455, London, England, ISBN 0 10 556761 2, May 2000. This report is also available from the OFWAT web site at http://www.open.gov.uk/ofwat/pubslist/pubsinfn.htm

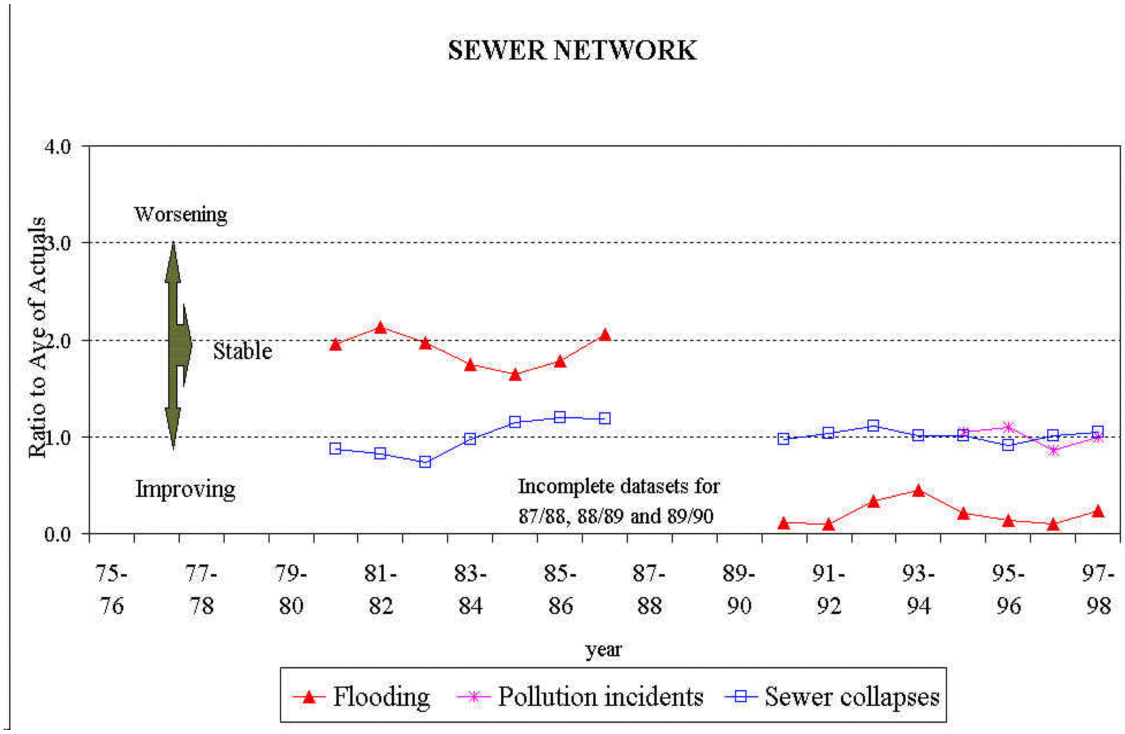

Figure 3-2. Summary analysis of trends of PIs for UK sewer mains for 1975-1998.[47]

Performance submission. OFWAT summarizes that information to create an industry picture of the water main and sewer networks covering the asset stock, and its valuation, condition, and its individual performance (see Tables 3-12 to 3-15).

Table 3-12. Kilometers of critical sewers by size in the UK (March 1998)

<=150 bore	<=300 bore	<=600 bore	<=900 bore	>900 bore	Total Stock
5,800	27,600	18,700	7,900	9,400	69,400

[47] Ibid.

Table 3-13. Summary of critical sewer condition by grade in the UK (March 1998)

Critical Sewers Asset Condition				
Grade 1	Grade 2	Grade 3	Grade 4	Grade 5
58%	18%	14%	8%	2%

Definition of Condition Grades:

Grade 1: No structural defects.
Grade 2: Minor cracking in brick sewers but no deformation or loss of bricks, line and level as built; for other sewers, some circumferential cracking or moderate joint defects.
Grade 3: Some deformation in brick sewers, displaced bricks, occasional connection defects; for other sewers, some deformation (up to 5 percent), cracking, fractures, joint defects or minor loss of level, or badly made connections.
Grade 4: Deformation in brick sewers up to 10 percent, some brick loss or moderate loss of level; for other sewers, deformation of up to 10 percent, cracked or fractured, or serious loss of level.

Table 3-14. Kilometers of non-critical sewer pipes in the UK by Diameter (March 1998)

<=150 bore	<=300 bore	=600 bore	Total Stock (km)
98,000	115,900	18,100	232,000

Table 3-15. Condition of non-critical sewer pipes in the UK (March 1998)

Non-Critical Sewers Asset Condition				
Grade 1	Grade 2	Grade 3	Grade 4	Grade 5
57%	20%	14%	7%	2%

Definition of Condition Grades:

Grade 1: No structural defects.
Grade 2: Minor cracking in brick sewers but no deformation or loss of bricks, line and level as built; for other sewers, some circumferential cracking or moderate joint defects.
Grade 3: Some deformation in brick sewers, displaced bricks, occasional connection defects; for other sewers, some deformation (up to 5 percent), cracking, fractures, joint defects or minor loss of level, or badly made connections.
Grade 4: Deformation in brick sewers up to 10 percent, some brick loss or moderate loss of level; for other sewers, deformation of up to 10 percent, cracked or fractured, or serious loss of level.
Grade 5: Collapsed or severely deformed sewers or missing inverts, or extensive areas of missing fabric/bricks.

The gross replacement cost of sewers with modern equivalent assets was estimated by the companies to be more than 96 billion. Around 9-10 percent of sewers were assessed to be in poor condition (condition grades 4 and 5). The aggregate reinvestment activity in kilometers on the critical sewer network over the last 8 years is summarized in Table 3-16 below.

Table 3-16. Kilometers of critical sewers recapitalized in the UK (by year)

Activity	90 - 91	91-92	92-93	93-94	94-95	95-96	96-97	97-98
Renovation	152	131	89	59	80	104	143	178
Replacement	3	165	146	111	68	76	105	92
New Sewers	384	507	455	334	350	228	272	212
Total Activity	539	803	690	504	498	408	520	482

Summary of PIs Used in Europe

Although the general concept of using PIs as a management tool is straightforward, the approaches to define, collect, and use PI information vary dramatically between the case studies from Europe. The PIs used in each case study were grouped into one of the following six categories:

- Table 3-17 lists indicators of plant and network size and type,
- Table 3-18 lists indicators of customer service,
- Table 3-19 lists indicators of water distribution system effectiveness and reliability,
- Table 3-20 lists indicators of wastewater collection system effectiveness and reliability,
- Table 3-21 lists indicators of environmental impact, and
- Table 3-22 lists indicators of infrastructure construction, maintenance, and rehabilitation cost-effectiveness.

Each table lists the PI used, identifies applicable type of infrastructure asset (water or wastewater), and identifies which organization utilizes it. As can be seen through these tables, the UK's OFWAT has adopted the most comprehensive list of PIs.

Table 3-17. Summary list of PIs related to plant size and type

Performance Indicator	Unit	Water	Wastewater	UK OFWAT	Reggio Italy	Six Cities
Plant capacity	volume/day	X	X	X	X	X
Length of pipes by type and section	length	X	X	X	X	X
Population served	count	X	X	X	X	X
System area covered	total area	X	X	X		
Cost - treatment cost per million gallons pumped	currency per volume	X		X		X
Cost of operations - total	currency	X		X		
Total value of system assets	currency	X	X	X		X
Value of system per length of pipe	currency/pipe	X	X	X		X
Quality of water at intake and treatment	varies	X		X		
Sewered area per mile of main	area/length		X	X		

Table 3-18. Summary list of PIs for customer service

Performance Indicator	Unit	Water	Wastewater	UK OFWAT	Reggio Italy	Six Cities
Complaints - number calls about interrupted service	count	X	X	X		
Complaints - water taste	count	X		X		
Complaints - other	count	X		X		
Complaints - odor	count	X	X	X		
Complaints per capita	complaints/person		X	X		
Complaints - water color	count	X		X		
Complaints - water pressure	count	X		X		
Number of new services connected, by customer type	count	X	X	X		
Service interruption time per customer	minute/consumer	X				X
Properties affected by unplanned interruption > 6 hours	count	X		X		
Service interruption - hosepipe bans	count	X		X		
Service interruptions - low flow restrictions	count	X		X		
Service interruptions - planned	count	X		X		
Service interruptions - unplanned	count			X		

Table 3-19. Summary list of PIs for water distribution system effectiveness and reliability

Performance Indicator	Unit	UK OFWAT	Reggio Italy	Six Cities
Pipe age	years	X		
Pipe material	varies	X		
Pipe diameter	varies	X		
Pipeline length in total, by type and section	unit length		X	
Pipe condition grade by type, size and location	score	X		X
Breaks	count	X		X
Breaks per pipe length per year (by area, severity, and type of pipe)	count/length/year	X		X
Distribution network delivery rate	cubic meter/length/year			X
Earning ability	billed/length			X
Fire delivery pressure	volume/second	X		
Leakage - average rate	volume/second	X	X	X
Leakage - total volume	cubic meter	X	X	X
Leakage - per unit length	volume/sec/length	X	X	X
Maximum daily demand/system capacity	volume/day	X		
Maximum head (pressure)	pressure	X		
Number of breaks, leaks, etc. repaired	count	X		
Per capita water consumption	volume/person	X		X
Percentage breaks, leaks, etc., repaired within x hours of notification	%	X		
Percentage of leakage versus total produced	%		X	
Percentage of total water volume metered	%		X	
Pressure	pressure	X		
Volume pumped, metered, and treated	unit volume		X	
Water billed - commercial consumption from billing data	liter/sec		X	
Water volume billed	cubic meter		X	

Table 3-20. Summary list of PIs for wastewater collection system effectiveness and reliability

Performance Indicator	Unit	UK OFWAT	Reggio Italy	Six Cities
Pipe condition grade by type, size and location	score	X		X
Average daily flow/max daily treatment capacity	%	X		X
Number of days volume of influent exceeded treatment plant capacity	count		X	X
Backups per capita	backups/person	X		
Blockages or stoppages/pipe length	count/unit length	X		X
Blockages/year/pipe length	count/year/length	X		X
Collapses/year/length	count/year/length	X		X
Pipe age	years	X		X
Pipe material	varies	X		X
Pipe diameter	varies	X		X
Length of pipe by section and type	length	X		X
Sewer flooding residences incidents, due to capacity	count	X		
Sewer overflows - combined	count	X		X
Sewer overflows - incidents due to sewer capacity	count	X		X
Sewer overflows - incidents due to blockages, etc.	count	X		X
Sewer overflows - incidents (other causes)	count	X		X
Sewer overflows/pipe length	count/length	X		X
Sewer overflows/1000 consumers	number/1000 consumers	X		X
Projected needed capacity in 5 years/current capacity	%	X		
Properties flooded internally by sewage - caused by blockages, sewer collapses, equipment failure, etc.	count	X		
Properties flooded internally by sewage as a result of overloaded company sewer	count	X		
Properties flooded internally by sewage - other causes	count	X		

Table 3-21. Summary list of PIs for environmental impact

Performance Indicator	Unit	Water	Wastewater	UK OFWAT	Reggio Italy	Six Cities
Water usage per capita	volume per customer	X		X	X	X
Pollution incidents/million residents	count/million residents		X	X		
Sewer bypasses	count		X	X		
Major and serious sewer overflows	count		X	X		
Sewer overflows, estimated volume	volume		X	X		
Sewer overflows/reporting period	count/reporting period		X	X		X

Table 3-22. Summary list of PIs for construction, maintenance, rehabilitation costs and effectiveness

Performance Indicator	Unit	Water	Wastewater	UK OFWAT	Reggio Italy	Six Cities
Cost - distribution cost per million gallons pumped	currency per volume	X		X		X
Cost - O&M costs	currency	X	X	X		X
Costs - cost per household or type of service	currency per house	X		X		
Costs - cost per length of new pipe installed by type, location and pipe diameter	currency per length	X	X	X		X
Costs - cost per length of repaired pipe installed by type of repair and pipe diameter	currency per length	X	X	X		X
Costs - per volume sold	currency/volume	X	X	X		X
Length of new line constructed	unit length	X	X	X		
Length of existing line rehabilitated	unit length	X	X	X		
Percentage of interruptions cleared in goal time	%	X	X	X		
Maintenance - pressure problems solved by company action	count			X		

Conclusions
Based on the review of the three case studies and European research papers, the following conclusions have been reached:

- The practice of using performance indicators as a management tool is not widespread or standardized across the different European countries. There are, however, cases where individual companies, regional consortiums, and national governments have used PIs to make management decisions about infrastructure investments. However, these companies and governments do not use a set of standard PIs. Only the UK is using a well-defined and nationally standardized approach. A set of well-defined and standard performance indicators is essential for comparing performance across countries, regions, and different systems.

- The PIs used in the case studies varied considerably, but could be grouped in the following categories:

  - Indicators of network type and size,
  - Indicators of customer service,
  - Indicators of water distribution system effectiveness and reliability,
  - Indicators of wastewater collection system effectiveness and reliability,
  - Indicators of environmental impact, and
  - Indicators of infrastructure construction and rehabilitation cost-effectiveness.

- The performance measurement system in the UK is the most developed and could serve as a model for the US. Although all of the case studies provided examples of how PIs could be used for intra-system, inter-system, and extra-system comparisons, only the UK's OFWAT uses PIs as one piece of information to approve rehabilitation plans and price rate changes. Therefore, companies must demonstrate via PIs how the plans improved the distribution or collection systems' serviceability to customers. If a particular water company is not able to prove this to OFWAT, they will not be allowed to use customer revenues to fund the future rehabilitation plans, and could even be denied a license to operate the water authority on the public's behalf.

Chapter 4
Recommendations for National Database of Performance Indicators for Drinking Water and Wastewater Infrastructure

In this chapter, a recommended list of performance indicators and an approach to handle the collection of the necessary data are provided. These recommendations are based on the assessment of the European experience, as well as similar US studies related to the use of performance indicators.

Proposed Indicators of Drinking Water and Wastewater Infrastructure Performance

It is recommended that the proposed indicators listed in Tables 4-1 to 4-6 be used as a basis for developing a standardized list of performance indicators. This list is based on the literature reviewed in this report and the two companion reports,

- Potable Water Distribution: An Assessment of European Approaches for Improving Operations and Maintenance, and

- Wastewater Collection: An Assessment of European Approaches for Improving Operations and Maintenance.

To develop a standardized list of PIs, it is recommended that the proposed list be provided to industry and academic and professional groups to verify its completeness and to establish common definitions for the selected PIs.

Although the general concept of using PIs as a management tool is straightforward, the approaches to define, collect, and use PI information vary dramatically between the case studies examined in Europe. The European experience also varies greatly from the efforts in the US.

Since one of the major goals of this study was to provide a framework for a standardized national database of performance indicators, the following is a proposed list of the PIs that would meet the requirements set out in the European case studies, as well as the following US organizations:

- The Governmental Accounting Standards Board (GASB) requires that state and local governments implement new accounting practices for infrastructure assets. This procedure involves the use of performance indicators. Specifically, state and local governments will have to:
  - maintain an up-to-date inventory of eligible infrastructure assets,
  - perform condition assessments of the eligible infrastructure assets and summarize the results using a standard measurement scale,

- ➤ estimate, each year, the annual amount to maintain and preserve the eligible infrastructure assets at the condition level established and disclosed by the government, and

- ➤ document that condition assessments are performed consistently at least every three years, and to provide reasonable assurance, through the use of the results of the most recent three condition assessments, that infrastructure assets are being preserved approximately at (or above) the condition level established and disclosed by the government.

- ◆ The USEPA requires municipalities holding National Pollutant Discharge Elimination System (NPDES) permits to monitor the performance of its sanitary sewers through its Capacity, Management, Operation and Maintenance Program (CMOM) for Municipal Sanitary Sewer Systems. This program requires NPDES permit holders to:

  - ➤ properly manage, operate, and maintain, at all times, all parts of the collection system that the permit holder owns or has operational control of,

  - ➤ provide adequate capacity to convey base flows and peak flows for all parts of the collection system that the permit holder owns or has operational control of,

  - ➤ take all feasible steps to stop and mitigate the impact of sanitary sewer overflows in portions of the system the permit holder owns, and to regain operational control as soon as possible, and

  - ➤ notify parties that have a reasonable potential for exposure to pollutants associated with the overflow event.

- ◆ The National Research Council's Committee on Measuring and Improving Infrastructure Performance provides recommended PIs in its report on measuring and improving infrastructure performance.

- ◆ The California State University's study (sponsored by the USEPA) provides an approach for evaluating and improving performance wastewater collection systems.

- ◆ The Water Environment Research Foundation provides a recommended approach to benchmark the performance of wastewater operations, collection, treatment, and biosolids management.

Based on the analysis of the requirements laid out in these documents and in the European case studies, a list of PIs has been proposed. The following tables contain a summary of the recommended PIs. Each table lists the PI, the appropriate units, the asset for which it applies (as shown in the highlighted columns), and references other studies that have applied it in the past. The PIs recommended in each study are grouped into one of the following five categories:

- Table 4-1 lists indicators of customer service,
- Table 4-2 lists indicators of water distribution system effectiveness and reliability,
- Table 4-3 lists indicators of wastewater collection system effectiveness and reliability,
- Table 4-4 lists indicators of environmental impact, and
- Table 4-5 lists indicators of infrastructure construction, maintenance, and rehabilitation cost-effectiveness.

Table 4-1. Recommended list of PIs for customer service

Recommended Performance Indicator	Unit	Water	Wastewater	UK OFWAT	Reggio Italy	Six Cities	NRC	WERF	Cal State	GSAB
Complaints - odor	count	X	X	X			X	X	X	X
Complaints - water color	count	X		X			X			X
Complaints - water pressure	count	X		X			X			X
Complaints - water taste	count	X		X			X		X	X
Complaints - other	count	X	X	X			X		X	X
Complaint calls/1000 customers	count /1000 customers	X	X	X		X	X	X		X
Complaints - total complaints	count		X			X	X	X		
Complaints - customer complaints by geographic area	count		X							X
Complaints - number of calls about interrupted service	count	X	X	X						X
Service interruption time/customer	minute/ consumer	X				X	X			X
Service interruption -properties affected by unplanned interruption > six hours	count	X		X						
Service interruption - hosepipe bans	count	X		X						
Service interruptions - low flow restrictions	count	X		X			X			
Service interruptions - planned	count	X		X						
Service interruptions - unplanned	count	X		X						

Table 4-2. Recommended list of PIs for water distribution system effectiveness and reliability

Recommended Performance Indicator	Unit	Water	Wastewater	UK OFWAT	Reggio Italy	Six Cities	NRC	WERF	Cal State	GSAB
Pipe condition grade by type and section	score	X		X		X		X	X	X
Breaks	count	X		X		X				X
Breaks/pipe length/year (by area, severity, and type of pipe)	count/length/year	X		X		X	X			X
Distribution network delivery rate	cubic meter/ length/year	X				X				
Leakage - average rate	volume/second	X		X	X	X				
Leakage - total volume	cubic meter	X		X	X	X	X			
Leakage/unit length	volume/sec/length	X		X	X	X	X			
Maximum daily demand/system capacity	volume/day	X		X						X
Number of breaks, leaks, etc. repaired	count	X		X			X			X
Number of new services connected, by customer type	count	X								X
Per capita water consumption	volume/person	X		X		X	X			
Percentage breaks, leaks, etc., repaired within x hours of notification	%	X		X				X		X
Percentage of total water volume by user category	%	X								X
Percentage of leakage vs. total produced	%	X			X		X			X
Percentage of total water volume metered	%	X			X					X
Projected water demand in 5 years/current capacity	%	X								X

Table 4-3. Recommended list of PIs for wastewater collection system effectiveness and reliability

Recommended Performance Indicator	Unit	Water	Wastewater	UK OFWAT	Reggio Italy	Six Cities	NRC	WERF	Cal State	GSAB
Pipe condition grade by type and section	score		X	X		X		X	X	X
Number of days volume of influent exceeded treatment plant capacity	count		X	X			X			X
Backups/capita	backups /person		X	X					X	X
Blockages or stoppages/pipe length	count/unit length		X	X		X		X	X	X
Blockages/year/pipe length	count/year/ length		X	X				X		
Collapses/year/length	count/year/ length		X	X		X		X	X	X
Collapses by pipe material, age, diameter and date of occurrence	count/type		X	X		X			X	
Projected needed capacity in 5 years/current capacity	%		X	X						X
Properties flooded internally by sewage - caused by blockages, sewer collapses, equipment failure, etc.	count		X	X						
Properties flooded internally by sewage - other causes	count		X	X						
Sewer overflows - incidents due to blockages, etc.	count		X	X				X		
Properties flooded internally by sewage, due to capacity	count		X	X				X		
Sewer overflows - incidents due to sewer capacity	count		X	X				X	X	
Sewer overflows - incidents (other causes)	count		X	X				X		
Sewer overflows/pipe length	count/length		X	X		X		X	X	
Sewer overflows/1000 consumers	number/1000 consumers		X		X	X		X		

Table 4-4. Recommended list of PIs for environmental impact

Recommended Performance Indicator	Unit		Wastewater	UK OFWAT	Reggio Italy	Six Cities	NRC	WERF	Cal State	GSAB
Water usage/consumer	volume/person	X		X			X		X	
Pollution incidents/million residents	count/million residents		X	X						
Sewer bypasses	count		X	X				X	X	
Sewer overflows - major and serious pollution incidents	count		X	X			X	X	X	
Sewer overflows - combined	count		X	X				X	X	
Sewer overflows, estimated volume	volume		X						X	
Sewer overflows/reporting period	count/reporting period of time		X	X		X	X	X	X	

Table 4-5. Recommended list of PIs for construction, maintenance, rehabilitation costs and effectiveness

Recommended Performance Indicator	Unit		Wastewater	UK OFWAT	Reggio Italy	Six Cities	NRC	WERF	Cal State	GSAB
Cost - total cost/pipe length	currency/volume	X	X	X		X				X
Cost - maintenance cost/pipe length	currency/length	X	X					X		
Cost - O&M costs	currency/length	X	X	X		X			X	X
Cost/capita of wastewater treated	currency/capita		X							X
Cost/household or type of service	currency/house	X	X	X						X
Cost/length of new pipe installed by type, location and pipe diameter	currency/length	X	X	X		X	X			X
Cost/length of repaired pipe by type of repair and pipe diameter	currency/length	X	X	X		X	X			X
Cost/volume sold	currency/volume	X	X	X		X	X			X
Crews/mile of pipe	crews/mile pipe	X	X						X	
Employees/pipe length	people/unit length	X	X					X		X
Failure rate	failures/time	X	X	X		X			X	
Blockage rate	count		X	X		X	X	X	X	
Infiltration and inflow ratio	%		X				X	X		X
Maintenance - average annual inspection rate by each method of inspection	inspection/time	X	X						X	
Maintenance - average service response time	hours		X							X
Maintenance - average time to restore operations	hours		X	X					X	
Maintenance - number of service calls completed	count	X	X							X

Table 4-5. Recommended list of PIs for construction, maintenance, rehabilitation costs and effectiveness

Recommended Performance Indicator	Unit		Wastewater	UK OFWAT	Reggio Italy	Six Cities	NRC	WERF	Cal State	GSAB
Maintenance - pressure problems solved by company action	count	X		X						
Percentage of interruptions cleared in goal time	%	X	X	X						X
Percentage manholes, lines inspected visually each year	%		X						X	
Percentage of force mains inspected annually	%	X	X	X					X	
Percentage of I/I flow eliminated	%		X						X	
Percentage of inflow sources eliminated	%		X						X	
Percentage of length maintained requiring repair	%	X	X	X						X
Percentage of repairs completed for each method	%	X	X						X	
Percentage of sewers inspected by CCTV each year	%		X	X					X	
Percentage of system cleaned annually	%	X	X	X					X	
Percentage of system inspected/year	%	X	X	X				X		
Percentage of system tested for smoke, dye	%		X						X	
Percentage rehabilitation completed	%	X	X	X					X	
Percentage time spent on maintenance	%	X	X						X	

Framework for Collecting Necessary Data

Most researchers and practitioners agree that data collection is expensive. Because data collection costs are so high, water authorities must avoid the unnecessary collection of data that will rarely, if ever, be used (e.g., the number of step irons in a manhole).

In the case of proactive rehabilitation planning, the data collected should support accurate predictions, via modeling, of pipe failures and impacts. Therefore, it is recommended that a water authority first collect only the minimum data required to establish a priority list of pipes in need of rehabilitation as shown in Table 4-6. Water authorities could then use one of a variety of models that take this data and develop a list of pipes prioritized by rehabilitation need (or risk of failure). This list could then enable them to limit expensive data collection efforts (e.g., manned pipe inspections, TV inspections, radar, etc.) to only those high-priority pipes.

The other data listed in Table 4-6 enables a water authority to complete the PIs recommended in this report and to conduct a more comprehensive analysis of the impact of different rehabilitation plans on costs, water quality, and service interruptions. It also enables managers to analyze the performance of their infrastructure assets and to compare that performance to other systems.

Table 4-6. Recommended data for pipe failure modeling, rehabilitation planning and for performance analysis

Category of Data	Type of Data	Data Essential for Failure Modeling
Data describing plant type, capacity, network size and asset value	Plant capacity	X
	Volume treated	X
	Volume billed	X
	Length of pipes by type	X
	Population served	X
	System area covered	
	Cost of operations — total and by activity (e.g., O&M, capitalization, etc.)	
	Total value of system assets — by type of asset	
	Quality of water at intake and treatment	
	Potable water storage capacity	
	Total employees	
Data describing significant pipe section characteristics	Pipe material	X
	Pipe diameter	X
	Date pipe installed	X
	Joint type	X
	Pipe section length	X
	Pipe depth	
	Pipe section design characteristic (force main, gravity feed, etc.)	
	Pipe condition (estimated or observed)	X
Data describing significant operational and maintenance factors	Water pressure (fire demand and average)	
	Customer complaints — by type	
	Water quality data	
	Nature and date of failure/leak/overflow (e.g., type, cause, severity)	X
	Nature and date of last repair (e.g., method, length, location, etc.)	
	Nature and date of maintenance operations by type	
	Construction method (e.g., fill type, location, etc.)	
	Crew size	

Table 4-6. Recommended data for pipe failure modeling, rehabilitation planning and for performance analysis

Category of Data	Type of Data	Data Essential for Failure Modeling
Data describing significant environmental and seasonal factors for entire system or for each pipe section	Soil type	
	Average soil moisture content	
	Average ground water depth	
	Average soil temperature and frost depth	
	Traffic and loading conditions	
	Location of co-located utilities	
Data describing significant cost and economic factors	Cost of corrective actions (by approach and pipe diameter)	
	Cost to replace pipe (by installation area and pipe diameter)	
	Discount rate	

Since proactive rehabilitation modeling requires a large volume of data to be integrated with some type of spatial analysis tool, water authorities rely on high-performance desktop computers. However, the collection, analysis, and communication of PI data requires a tool that enables water authorities to share PI data in order to benchmark its performance. The world wide web (www) provides an excellent mechanism to enable water and wastewater authorities to collect the data required for calculating ranges for PIs, and for communicating the results to participating municipalities and concerned stakeholders. Figure 4-1 presents a framework for collecting the necessary data and communicating results via the www.

A national database of standard PIs is envisioned. This database would not only contain raw data, but would establish ranges for each PI (e.g., 25th percentile to 75th percentile). In general, it is recommended that the national database have the following characteristics:

- Participating municipalities would voluntarily submit raw data in exchange for analyzed PIs and intra-system comparisons.
- The tool would consist of an easy-to-use www-based interface for both data entry and PI analysis.
- The required data elements and resulting PIs would be clearly defined.
- Users would have a secure connection and the ability to restrict the release of proprietary information.

- Participating municipalities would be able to maintain historical data submissions.

Recommendations for Next Steps

The information provided in this report is only intended as a framework for going forward. It is recommended that the information in Tables 4-1 to 4-6 be used as a basis for developing a web-based survey of industry, state, and local government officials, and academic and professional groups. The purpose of the survey would be to select the most important PIs, create standard definitions, and to verify the core data elements necessary to support the selected PIs.

The results from this survey could be used as a basis to convene an expert steering committee to provide direction to the development and use of the database. Participation by representatives of industry, local government, and water authorities is key.

Once standard definitions are developed, volunteer water authorities could provide the data necessary to develop a statistically significant database of infrastructure performance indicators.

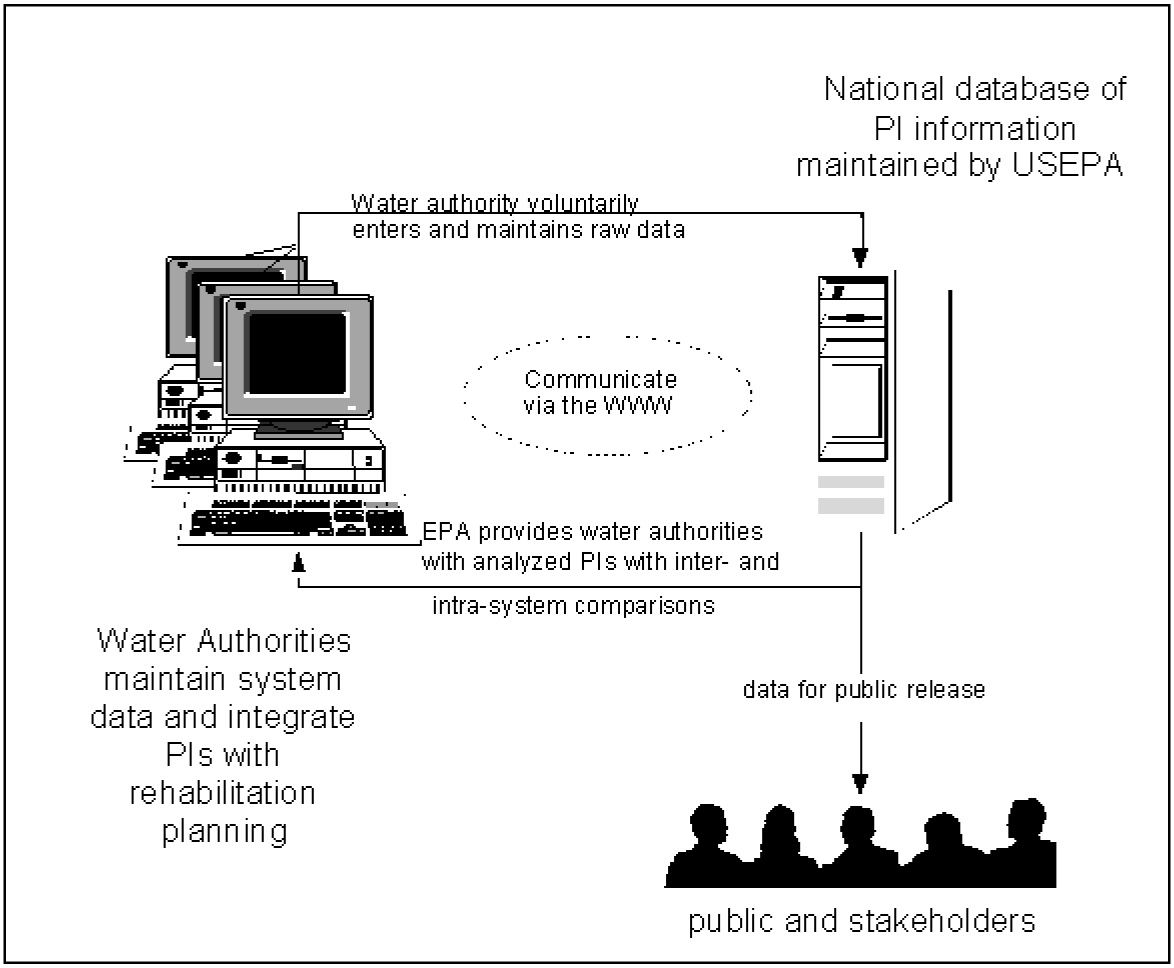

Figure 4-1. Framework for collecting and communicating PI data.

Appendix A - References

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Appendix B - List of European Experts

Table B-1. List of European potable & wastewater infrastructure experts

Name	Contact information	Areas of expertise
Dr. Peter Stahre	Director Malmo Water and Wastewater Works S-205 80 Malmo, Sweden Tel: 9-011-46-4034-1623 Fax: 9-011-46-4034-1448 E-mail: peter.stahre@malmo.se	Potable and wastewater infrastructure
Mr. Keith Edwards	C3, MC WGD Network Technology Manager Anglian Water Services Ltd. -Henderson House Lancaster Way, Ermine Business Park UK-PE18 6 XZ Huntingdon Tel: 9-011-44-1480-323996 Fax: 9-011-44-1480-323993 E-mail: kedwards@anglianwater.co.uk	Industry perspective and modeling
Dr. Gerald M. A. Jones	WRC. Inc. 2655 Philmont Ave. Huntingdon Valley, PA 19006 Email: Gerald Jones/WRcPLC@WRcPLC	Potable and wastewater infrastructure
Dr. Paul Conroy	WRC. Inc. 2655 Philmont Ave. Huntingdon Valley, PA 19006 Email: conroy@wrcplc.co.uk	COST information and modeling
Prof. Dr. –Ing Raimund Herz	Dresden University of Technology Chair of Urban Engineering Nürnberger Straße 31A, 5.OG 01187 Dresden, Phone: (0351) 463-2383 Fax: (0351) 463-7730 Email: herz@rcs.urz.tu-dresden.de	Infrastructure modeling
Dr. Sveinung Saegrov	SINTEF Civil and Environmental Engineering, N-7034 Trondheim, Norway Tel: 9-011+47-73-592349 Fax: 9-011+47-73-592376 E-mail: sveinung.sagrov@civil.sintef.no	Overview of European Systems