United States
Environmental Protection
Agency

Office of Water (4601M)
Office of Ground Water and Drinking Water
Total Coliform Rule Issue Paper

Distribution System Inventory, Integrity and Water Quality

January 2007

PREPARED FOR:

U.S. Environmental Protection Agency
Office of Ground Water and Drinking Water
Standards and Risk Management Division
1200 Pennsylvania Ave., NW
Washington DC 20004

PREPARED BY:

American Water Works Association

Background and Disclaimer

The USEPA is revising the Total Coliform Rule (TCR) and is considering new possible distribution system requirements as part of these revisions. As part of this process, the USEPA is publishing a series of issue papers to present available information on topics relevant to possible TCR revisions. This paper was developed as part of that effort.

The objectives of the issue papers are to review the available data, information and research regarding the potential public health risks associated with the distribution system issues, and where relevant identify areas in which additional research may be warranted. The issue papers will serve as background material for EPA, expert and stakeholder discussions. The papers only present available information and do not represent Agency policy. Some of the papers were prepared by parties outside of EPA; EPA does not endorse those papers, but is providing them for information and review.

Additional Information

The paper is available at the TCR web site at:

http://www.epa.gov/safewater/disinfection/lt2/compliance.html

Questions or comments regarding this paper may be directed to **TCR@epa.gov.**

Table of Contents

Distribution System Infrastructure Inventory and Integrity

Abstract

This white paper reports on the availability of data about distribution system infrastructure, and the ability to answer selected questions using these data. The paper does not address water quality, policy needs, or potential research projects. Water distribution systems comprise complex networks of infrastructure components. Currently, available data provide more information on distribution systems than existed a decade ago. At the national level, data with which to describe distribution systems is good, but the information has not in all cases been verified. The data reported are mainly from recent AwwaRF reports, AWWA's Water Industry Data Base and Water://Stats surveys, and EPA's Community Water System Survey (CWSS) and Needs Survey. Data on the extent of water mains, finished water storage, hydrants, some types of valves, and customer service lines are generally good. Very little data are available on other components of distribution systems or on premise plumbing. The practice of condition assessment is intended to support asset management programs rather than general conclusions about the overall condition of the nation's water distribution system infrastructure. Implementation of asset management systems that require condition assessment varies from utility to utility – some utilities have complex data systems, while many utilities rely on paper files, maps, and the experience of the utility staff.

Distribution System Infrastructure Inventory and Integrity

1.0 Introduction

The purposes of this white paper are to report on the availability of data about distribution system infrastructure and to summarize answers to selected questions that can be supported by the data. In simple terms the purpose of the water distribution system infrastructure is to supply water to all customers at sufficient pressure and volume to provide for their needs as well as for fire suppression (water quantity aspects), while also protecting the quality of the water as prescribed by various standards (water quality aspect). It is important that distribution systems deliver water reliably and protect the quality of the water that is delivered (National Research Council, 2006). These water distribution systems involve complex networks of infrastructure components consisting of pipes, joints, valves, and other appurtenances. In addition, water travels through service lines and premise plumbing systems before arriving at the customer's tap.

Throughout the paper, infrastructure issues are discussed using terminology that is not in all cases standardized. When terms are introduced, working definitions are presented, and acronyms are explained when they appear.

The term "inventory" refers to the identification, location, and description of distribution system components such as pipe segments, valves, and other parts. The term "condition" refers to appraisal of the current physical integrity of a component compared to its original designed condition. In this instance "physical integrity" of a component is a measure or estimate of flaws, defects, or decay that could reduce its service life (time from installation to replacement), as compared to original physical condition.

While distribution systems may affect drinking water quality and while water quality may affect health, this paper does not address these possible effects. It also does not make recommendations about policies or needed research. The paper is principally focused on reporting about sources and extent of data that is available and how it bears on the following questions:

- How much and what types of pipe and fittings are in service today?
- How much and what types of pipe are being installed and renewed today?
- How many and what types of storage tanks exist?
- How many and what types of fire hydrants and valves are in service today?
- How is the condition of distribution systems assessed? What is the knowledge base about the condition of distribution systems?
- What other appurtenances can be assessed?

The knowledge base about distribution system infrastructure has improved greatly since the 1986 Amendments to the Safe Drinking Water Act (SDWA). Prior to that date, neither individual utility studies nor national surveys were very extensive in their reporting of infrastructure data. The emergence of electronic database and Geographic Information System (GIS) technology, along with recent waves of activity in vulnerability assessment and "asset management" have led to more interest in conducting infrastructure inventories. An inventory of a distribution system comprises identification, location, and description of components such as pipe segments, valves, and other appurtenances.

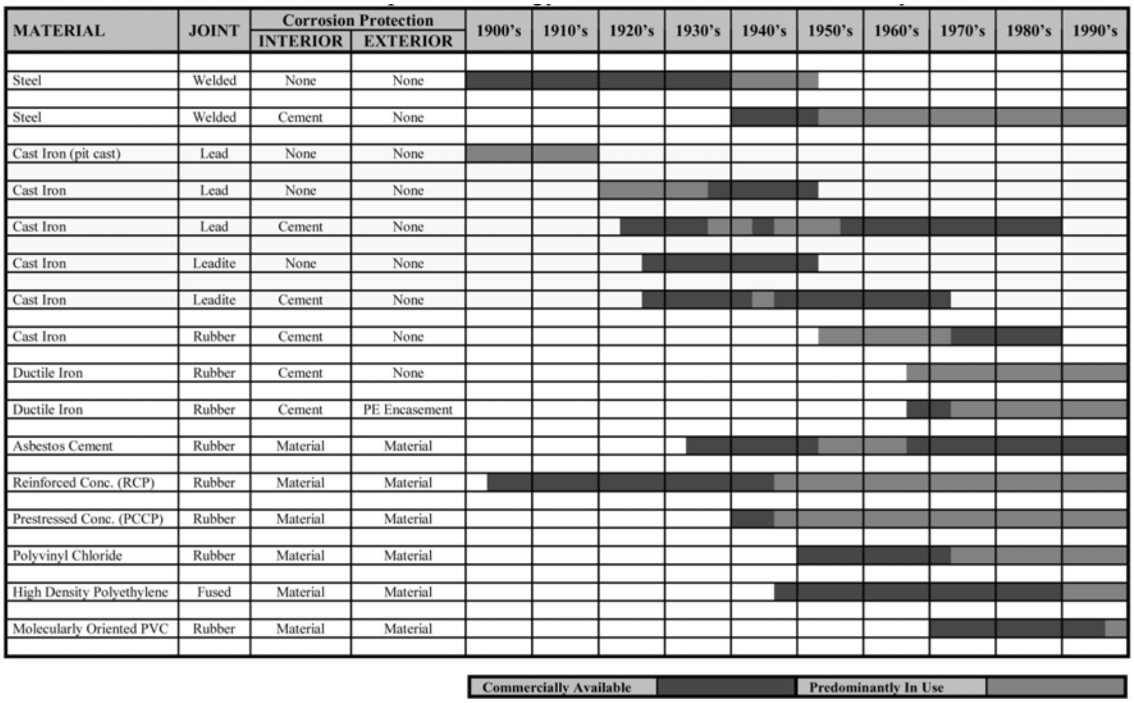
Although extensive distribution system infrastructure data were not published prior to about 1986, utility surveys by the American Water Works Association (AWWA) actually began much earlier. Additionally, prior to about 1960 the literature contains a number of short papers about problems and remedies with cast iron water mains. During the 1970s more information and basic data were collected, but the data available increased more rapidly after 1986. The data available has been collected using different means. The primary categories of data are AWWA and EPA surveys and AwwaRF case studies of one or more utilities. Other studies have been published, but they rely on data from these primary sources. A list of references is available in Grigg (2004), which provides a synthesis of the information available on water distribution system infrastructure.

2.0 Buried Infrastructure Challenges Facing the Water Industry

The buried infrastructure challenges facing the water industry were summarized in one of a series of papers that were prepared for EPA to provide information about potential distribution system requirements being evaluated under the 6-year review of the Total Coliform Rule (TCR) (American Water Works Service Co., Inc., May 2002).

The paper outlines how most distribution pipes installed from the late 1800s to the late 1960s in the United States were of cast iron. It describes how casting technologies changed from pit casting to centrifugal casting, which made a thinner pipe wall and lighter pipe possible. The paper also outlines how cement mortar pipe lining improved resistance to internal corrosion, how jointing changed from lead to a plasticized sulfur cement compound called "leadite," and how "leadite" joints failed more often than the older lead joints. Further improvements in jointing occurred with the introduction of rubber gaskets. The next major advancement was the development of ductile iron pipe, which has a different internal metallic structure due to the metal's graphite content. Then, polyvinyl chloride (PVC) and high-density polyethylene (HDPE) pipe technologies were developed, that are not subject to the corrosion processes that affect iron pipe. The paper does not discuss reinforced concrete pipe or prestressed concrete cylinder pipe (PCCP). Some PCCP has experienced catastrophic failures due to production processes that led to failure of reinforcing bands. The paper does not discuss the use of asbestos cement (AC) pipe, which was significantly used in the 1950s and 1960s but was discontinued due to concerns over asbestos. However, the paper does contain a diagram, which is reproduced here as Figure 1, which shows the eras when asbestos cement and other types of pipe were predominant.

Figure 1. Timeline of Pipe Technology in the U.S. in the 20th Century (American Water Works Service Co., Inc., 2002)



MATERIAL	JOINT	Corrosion Protection INTERIOR	Corrosion Protection EXTERIOR
Steel	Welded	None	None
Steel	Welded	Cement	None
Cast Iron (pit cast)	Lead	None	None
Cast Iron	Lead	None	None
Cast Iron	Lead	Cement	None
Cast Iron	Leadite	None	None
Cast Iron	Leadite	Cement	None
Cast Iron	Rubber	Cement	None
Ductile Iron	Rubber	Cement	None
Ductile Iron	Rubber	Cement	PE Encasement
Asbestos Cement	Rubber	Material	Material
Reinforced Conc. (RCP)	Rubber	Material	Material
Prestressed Conc. (PCCP)	Rubber	Material	Material
Polyvinyl Chloride	Rubber	Material	Material
High Density Polyethylene	Fused	Material	Material
Molecularly Oriented PVC	Rubber	Material	Material

3.0 AWWA and AwwaRF Studies and Surveys

The most comprehensive inventory information on distribution systems is furnished by AWWA's Water Industry Data Base and Water://Stats surveys. In addition, AWWA and the AWWA Research Foundation (AwwaRF) have conducted a number of studies about distribution systems, both relying on existing data and on limited surveys and/or case studies. These studies report on problems and management practices by utilities, and taken together, provide a valuable set of data about distribution system infrastructure.

3.1 AWWA and AwwaRF Studies

Table 1 provides a list of AWWA and AwwaRF studies that contain data about distribution system infrastructure.

These and other studies are summarized in Grigg (2004), which also presented information collected from approximately 50 utilities in three workshops, site visits, and surveys. Results of this canvassing showed that use of technologies is advancing in asset management, but a very significant gap remains between utilities that use sophisticated technologies and practices and others that do not. Examples of leading practices include: materials analyses, comprehensive condition assessment, use of GIS, maintenance scheduling, databases to manage pipe data and track leaks and main breaks, capital improvement planning for renewal, and use of trenchless renewal methods.

Table 1. List of AWWA and AwwaRF studies on distribution system infrastructure

Study author	Summary
O'Day et al. (1986)	Surveyed six utilities (New York, Denver, Philadelphia, Louisville, East Bay, and Kenosha). Report contains often-cited information about failure mechanics, condition assessment, management methods and other topics.
Deb et al. (1990)	Studied seven utilities and surveyed 35 utilities about renewal practices. Most appurtenances were replaced rather than rehabilitated. Valves and hydrants were both replaced and rehabilitated. Shows that renewal is practiced, especially in large utilities, but other than cleaning and lining, new technologies were not in widespread use.
Kirmeyer et al. (1994)	Surveyed twenty utilities in 1992. Also summarized AwwaRF's three expert workshops on distribution systems, held in 1990, 1991, and 1992. This research needs section of this report is often cited for its presentation of distribution system statistics.
Stratus Consulting (1998)	AWWA commissioned an independent assessment of distribution system needs that led to a 20–year estimate of $325 billion.
Deb et al. (1998)	This report about a prioritization model also reviewed distribution system statistics.
Deb et al. (2000)	Surveyed 37 utilities about O&M, including European utilities. Leak detection was the least common maintenance activity, among tasks such as hydrant flushing and testing. 81% had corrosion control procedures and 60% had procedures for main breaks. 70% had maintenance history databases. While statistics show that utilities engage in the activities, they do not reveal the extent to which they implement them.
Cromwell et al. (2001a)	Surveyed 20 utilities and reported needs of more than $250 billion over the next 30 years to replace pipes and infrastructure. This does not include more than $12 billion per year that utilities spend on infrastructure repairs or Safe Drinking Water Act compliance.
Cromwell et al. (2001b)	Benchmarking and process comparisons of asset management practices between 15 North American and 2 Australian utilities.
Deb et al. (2002)	Found from WATER:\STATS that in 1995 there were 23-breaks/100 miles/year. Break rates in Europe are higher, on the order of 50-breaks/100 miles/year. The data show scatter in break rates, especially for small utilities.
Grigg (2004)	Collected and synthesized data from approximately 50 utilities in three workshops, site visits, and surveys

While these are examples of leading practices, the effectiveness and extent to which they are used varies widely. Two utilities may report in a survey that they use a computer-based maintenance management system, but one may have a system that is highly integrated with their asset management strategy and yielding significant benefits, while the other may have just purchased a stand-alone work order management system off the shelf, which limits the benefits obtainable in asset management unless it is used in an integrated fashion. So far, the extent to which utilities are benefiting from these technologies is mostly contained in case studies, such as those in the reports given in Table 1.

While more recent survey data is available, the Kirmeyer et al. (1994) report for AwwaRF offers a comprehensive view and useful statistics because a main activity of the study was to process and analyze the available AWWA and utility data about distribution system infrastructure, whereas data from more recent AWWA surveys requires further analysis to determine trends and conclusions. The study's authors conducted their own surveys, used the AWWA Water Industry Data Base (WIDB) survey data, and visited utilities. Tables 2, 3, and 4 are based on the Kirmeyer et al. (1994) study, and present in a capsule form key data about inventories and management practices. The more recent surveys confirm the basic data in these tables.

The data in Table 2 was compiled using a number of approaches. First, data was compiled from results of AwwaRF projects available at the time, including three expert workshops on distribution systems. Twenty utilities were studied in depth. The expertise of a project advisory committee that included experts who had completed past projects was tapped. And, a special workshop during AWWA's 1992 Distribution Systems Symposium was conducted to collect data and opinions from additional utilities. The data in Table 2 is described by Kirmeyer et al. (1994) as based on the above project information, AWWA's Water Industry Data Base (predecessor to AWWA's Water://Stats database), and reports of the Water Industry Technical Action Fund (WITAF).

Table 2. Statistics of U.S. distribution systems (Kirmeyer et al., 1994)

Distribution system elements	Project findings
Estimated length of distribution piping	880,000 miles
Estimated replacement value of piping	$348 billion
Condition of piping more than 30 years old	28% excellent, 43% good, 26% fair, 3% poor (these composite figures are based on surveys of 20 utilities and their reports of condition for water quality, structural performance, and hydraulic performance)
Estimated number of pipe breaks	237,600 breaks/year (27-breaks/100 mi/yr) (note: this is a different data set than Deb et al., 2002, which reported 23-breaks/100 mi/yr)
Primary types of existing piping	48% cast iron, 19.2% ductile iron, 15.1% AC*
Estimated new piping	13,200 miles/year (DIP*47.7%. PVC* 38.7%), CPP* 12.5%) (cost $2.8 billion per year)
Estimated pipe replacement	4,400 miles per year
Value of replacement	$1.742 billion per year
Lead service lines	2.3 to 5.1 million
Cost to replace lead service lines	$10-14 billion
Fire hydrants	5.85 million
Percent of O&M* budgets to T&D*	36.2%
Total O&M budget to T&D	$4.5 billion per year
Inadvertent system losses (defined as losses other than "authorized" losses, e.g., leaks, inaccurate meters, etc.)	10%
Cost of water losses	$2.8 billion per year

* Key to table: AC = asbestos-cement; DIP = ductile iron pipe; PVC = polyvinyl chloride; CPP = concrete pressure pipe; O&M = operations and maintenance; T&D = transmission and distribution.

As shown above, Kirmeyer et al. (1994) estimated that some 2.3 to 5.1 million lead service lines are still in service. Replacement of the utility portion was estimated to cost $3.4 to $5.1 billion. Complete replacement of the utility and residential portions of existing lead service lines was estimated to cost $10 to $14.1 billion.

Table 3 was prepared from a survey question posed by Kirmeyer et al. (1994) that asked utilities to list the five most common causes of main breaks. The data did not distinguish between types of materials. Table 4 is based on survey responses to the question: "What are your criteria for deciding whether a particular section of pipe is to be replaced?" Note that the top criterion for pipe replacement is "number of leaks or breaks." This might be construed to imply a reactive approach, but some would argue that leaks and breaks are, in fact, the most cost-effective and integrated measures of pipe condition that are available to support a predictive approach to replacement (Cromwell, 2001b; Hughes, 2002).

Table 3. Causes of main breaks (Kirmeyer et al., 1994)

Causes of main breaks	Percent of utilities reporting
Materials/deterioration	55
Weak joints	35
Earth movement or settling	30
Freezing	30
Internal corrosion	25
Corrosive soils	25
Construction or utility digging	25
Stray DC current	20
Seasonal changes in water temperature	15
Heavy traffic load	10
Tidal influences	5
Changes in system pressure	5
Water hammer	5
Air entrapment	5

Table 4. Criteria for pipe replacement (Kirmeyer et al., 1994)

Criteria for pipe replacement	Percent reporting
Number of leaks or breaks	75
Age of pipe	45
Low flow	40
Condition or type of material	30
Size changes required	30
Water quality	15
Soil condition	15
Location	10
Street construction work	10
Elimination of dead ends	5
Amount of damage by leaks/breaks	5

A survey by CH2M Hill was reported at AWWA's 1985 Distribution System Symposium and described by (O'Day et al., 1986). This limited survey is significant in that it demonstrates the variability in distribution system management actions taken among small, medium, and large utilities. Percentages of reported actions are shown in Table 5. The data show the expected results that small utilities participated in infrastructure management activities to a lesser extent than larger utilities.

Table 5. Percentage of surveyed utilities practicing management activities shown (O'Day et al., 1986)

Management activity	Small < 5 mgd	Medium 5-50 mgd	Large > 50 mgd
Leak detection surveys	16	19	40
Method to determine replacement need	63	77	100
Computer model of system hydraulics	48	58	90
Reports of main breaks	27	66	80
Steps to remove scale and tuberculation	13	31	30
Revenue to finance renewal program	59	69	80
Budget and planning for replacement	48	67	90

3.2 AWWA's Water://Stats Database

AWWA's Water://Stats database (AWWA, 2004) is the most current survey of the drinking water industry produced by AWWA. AWWA's water industry surveys began before 1900, and the information they provide can serve as a historical reference and current source of information about water distribution infrastructure.

A compilation of the surveys since 1945 was provided by AWWA (Keeley, 2003). It shows that surveys were conducted every five years from 1945 through 1970, then surveys were conducted more frequently. The number of utilities responding varies from a low of 211 (1985 survey) to a high of 1,397 (1981 survey), with the average between 1945 and 1985 being 770 utilities (Seidel, 1985). Grigg (1988) reviewed data in the 1984 survey. Prior to about 1980, the surveys focused on water production and rates. Survey data and associated reports show that management attitudes have changed, requiring the collection of different data. For example, discussion at the 1985 AWWA annual conference stressed the need for capital management programs to sustain infrastructure (O'Day et al., 1986). However, the attitude among 33 of the large utilities surveyed was that O&M expenditures were adequate to maintain reliability even though 23 of them had reported some deferred maintenance.

The modern survey effort was launched as a joint AWWA/AwwaRF project in 1989/1990 as the Water Industry Data Base (WIDB). It was intended to develop detailed profiles of individual utilities that could also be aggregated to profile the large system segment of the industry (Cromwell et al., 1990). The initial survey was sent only to the 3,000 water systems that serve more than 10,000 people. Some 1097 responses were obtained, representing only 2% of community water systems, but about half of the total population served by community water systems (112 million). Respondents reported a total of 436,000 miles of distribution pipe, broken down as: 50% cast iron, 20% ductile iron, 15% AC pipe, and 15% other materials. Pipe replacement rates were 0.6%/yr versus 1.6%/yr for pipe expansion. The survey also documented the presence of 11,000 storage facilities, broken down as: 60% steel tanks, 15% concrete tanks, and 20% below-ground clearwells and reservoirs.

The AWWA/AwwaRF Water Industry Data Base effort was renamed WATER://STATS in 1996, and since then, surveys focus on specific subjects, such as finance (1999 survey of 672 utilities), distribution systems (2002 survey of 337 utilities) and rates (2004 survey of more than 250 utilities).

The 2002 Water://STATS Distribution Survey (AWWA, 2004) includes a set of questions that focus on the distribution system rather than on general utility profiles. It was sent to 3,000 water utilities and the response rate was 11%. Data were collected between June 2002 and April 2003. The survey covers pipe materials, valves, fire hydrants, finished water storage facilities, corrosion control, pumping capacity, metering, customer service lines, water auditing, leakage management and infrastructure needs. Water audit and leakage management data is in a format developed in 2000 by the International Water Association.

The 337 utilities that were surveyed served 59,389,902 in population, and had 14,339,261 customer service lines, and 146,435 wholesale connections. Total length of pipe was 202,000 miles for the population served, and if increased by ratio to current total population (2004 US population of 292.5 million), it reaches 980,000 miles, a figure that is roughly comparable to the 1992 estimate of 880,000 miles (Table 2, above) drawn from the prior WIDB survey (Kirmeyer et al., 1994). It is noted, however, that both WIDB and WATER://STATS results indicate that the length of pipe per capita varies with system size, so using overall averages to extrapolate is only a broad approximation.

Data available are summarized in the next section. They include utility information, types of services provided, pipe material, finished water storage, water conveyance, valves, fire hydrants and flushing, customer metering, customer service lines, customer service lines responsibilities, corrosion control, water supply auditing, leakage management, and infrastructure.

More analysis is needed to separate wholesale and retail customers before ratios such as miles of line and valves per capita can be compared meaningfully. Also, the data must be processed to homogenize values and to facilitate comparison. Data in the 2002 survey do not show expansion and replacement by pipe type.

The data from the 2002 survey might suggest that both pipe expansion and replacement have slowed since the WIDB-based estimates by Kirmeyer et al. (1994). But interpretation of these broad extrapolations should not be stretched that far. In contrast, the more detailed inventory of distribution system components, profiled in the 2002 Water://Stats Survey is useful in providing deeper insights into more parameters.

Table 6. Comparison of population-based extrapolations to national totals from AWWA 1989/90 WIDB survey results and AWWA 2004: Water://Stats 2002 survey

Item	WIDB (1097 utilities) (Kirmeyer et al., 1994)	Water://Stats 2002 (337 Utilities) (AWWA, 2003)
Miles of pipe	880,000	980,000
Expansion per year, miles	13,200	5,100
Replacement per year, miles	4,400	3,590

Shown below are:

- A matrix showing availability/quality of the data available for each subject;
- An assessment of the capability to disaggregate national figures into regional and/or system size categories; and,
- An analysis of whether trends can be observed for regions or system sizes

Table 7. Matrix of data availability in AWWA 2004: Water://Stats 2002 survey

Data	Available	Quality of data
Pipe data	Yes	Data on miles of pipe by type is very detailed. Data on expansion and renewal does not specify pipe materials. Data on pipe condition and on failure mechanics is only anecdotal.
Finished water storage tanks	Yes	Inventory data is very detailed by type of tank. Condition data is not available. Data is available on maintenance.
Joints and gaskets (not included)	No	Data not available.
Hydrants	Yes	Inventory data and data on maintenance and exercising is detailed.
Customer service lines	Yes	Inventory data on customer service lines is provided. Data is available on type of line, but not on condition of lines.
Distribution system meters	No	No data is available.
Customer meters	Yes	Inventory data is provided, but no data on condition or reliability is available.
Valves (gate, butterfly, PRV)	Yes	Data on number of gate, butterfly, and pressure reducing valves is available, but condition data is not available.
Pumps	No	Data not available
Backflow preventers	No	Data not available in Water://Stats.
Other system appurtenances (e.g., blowoffs, air release valves)	No	Data not available

Table 8 presents the results from the 2002 Water://Stats data. The raw data could be disaggregated by size of pipe and size of system, But such assessment was beyond the scope of this paper to address. Note that the data on percent of total miles of pipe is based on averages of reported data by utilities of this statistic, and is not computed from the data on miles in place as reported in Table 8. This method of computing the averages will produce small differences in the right hand column of Table 8, but is not significant in terms of estimating the national inventory of pipe.

Table 8. Pipe Inventory of AWWA 2004: Water://Stats 2002 Survey

Pipe material	Miles in place (WaterStats, 2002)	% of total miles of pipe * (as reported by utilities)
Ductile iron, CML	35,118	19.7
PVC	29,835	16.6
Asbestos cement	30,484	15.2
Cast iron, unlined	37,433	14.4
Cast iron, CML	34,039	14.4
Ductile iron, unlined	9,886	4.3
Steel	7,821	3.8
Other 1	3,071	2.4
Concrete pressure	4,774	1.9
Polyethylene	1,377	1.1
Other 2	2,294	0.3
Other 3	977	0.2
Other 4	5,049	0.1
Misc./unknown	6,000	N/A
Total	202,158	*

***** (Percentages do not add to 100 because of data inconsistencies).

Responses for the "other" categories were: galvanized iron, HDPE, wrought iron, black iron, copper, steel cylinder pipe, plastic, cement-stove, fiberglass (Permastrand), concrete lined steel cylinder, steel, arch concrete masonry, polybutylene, and unknown. Utilities listed different materials for "Other (1, 2, 3, 4)," and these cannot be correlated with pipe material type, such as HDPE, black iron, etc.

Finished water storage tank data from the 2002 Water://Stats survey show a total of 4,929 storage tanks among the surveyed utilities. The types of tanks are shown in the Table 9. Capacities are also reported, but quality of the data in the survey tables should be assessed before totals can be reported. Some utilities may have reported capacity in gallons, rather than millions of gallons, and an analysis of the data should be carried out before total capacities are reported. Hydrant data from the 2002 survey are reported in Table 10. Data on repairs and inspections are on an annual basis.

In Table 11, data on customer service lines are shown. The total number of lines surveyed was 14,120,646, which serve a population of over 59 million customers. Extrapolation of the reported value of 3.3% for lead pipe suggests that there are some 2.3 million lead service lines in use, and this estimate compares well to the estimate by (Kirmeyer et al., 1994) of 2.3 to 5.1 million lead service lines still in service.

Table 9. Storage facilities (AWWA 2004: Water://Stats 2002 survey)

Storage tank type	Number in service
Welded ground storage	1,395
Welded elevated	910
Reinforced Concrete	577
Basins	522
Welded standpipes	427
Other	406
Wirewound	353
Bolted ground storage	224
Bolted standpipes	47
Tendons	38
Composite	30
Total	4,929

Table 10. Hydrant data (AWWA 2004: Water://Stats 2002 survey)

Item	Profile data
Hydrants in system, dry barrel	959,437
Hydrants in system, wet barrel	415,751
Total hydrants	1,375,188
Hydrant repairs, dry barrel	77,082
Hydrant repairs, wet barrel	15,852
Hydrant inspection, dry barrel	614,277
Hydrant inspection, wet barrel	216,051
Miles of pipe flushed annually	67,655
Hydrants flushed	437,696

Table 11. Customer service lines (AWWA 2004: Water://Stats 2002 survey)

Service line type	Percent *
Copper pipe	56.3
Lead pipe	3.3
Polybutylene	2.4
Polyethylene	11.4
Polyvinyl chloride	5.8
Steel	1.5
Cast iron	1.2
Galvanized	8.0
Asbestos cement	0.2
Other 1	1.8
Other 2	0.3

* Percentages do not sum to 100 due to inconsistencies in reporting of data.

Reported in "other" categories are: ductile iron, plastic, brass, CAI, DUC, wrought iron, Tubelog, cement lined wrought iron, KITEC (aluminum/PE composite), Tuballoy, and HDPE. Data summaries do not clearly distinguish which are "Other 1" and "Other 2."

Data in Table 12 represents the data available on the valve types and size in service as reported by the surveyed utilities.

Table 12. Valve data (AWWA 2004: Water://Stats 2002 survey)

Valve type	Number in service
Gate valves, 12 in and smaller	2,575,071
Gate valves, larger than 12 in	200,988
Butterfly valves, 12 in and smaller	92,110
Butterfly valves, larger than 12 in	58,421
PR valves, 12 in and smaller	37,993
PR valves, larger than 12 in	804

Other equipment and appurtenances (general data is not available on these elements of the distribution system):

- Pumps
- Backflow preventers
- Other system appurtenances (e.g., blowoffs, air release valves)
- Joints and gaskets
- Distribution system meters
- Customer meters

The surveyed population of 59,389,902 is about 20% of the national population in 2004. Table 13 summarizes data and extrapolates it to the year 2004 population, simply on the basis of population. The tenuous nature of such extrapolation should be respected.

Table 13. Summary of population extrapolations from AWWA 2004: Water://Stats 2002 survey

Dist. system infrastructure components	Surveyed population served of 59.4 million	Extrapolated to 2004 U.S. population of 292.5 million
Pipe miles	202,158	995,644
Storage tanks	4,929	24,276
Total hydrants	1,375,188	6,772,910
Total service lines	14,120,646	69,545,307
Total valves	2,965,387	14,604,767
Expansion, miles	1,052	5,181
Replacement, miles	740	3,645

4.0 EPA Surveys and Other Federal Government Analyses

Studies sponsored by the Environmental Protection Agency (EPA) include surveys and case-based research. Surveys were produced to support needs studies for infrastructure funding, and case-based research studies include studies by the Cincinnati and Edison Laboratories, and comprehensive reports such as Smith et al. (2000).

EPA's Community Water Systems Survey is based on an extensive, stratified sample of systems (EPA, 2002a). It includes estimates of miles of pipe in place (by diameter), miles replaced, and replacement costs. The survey also includes information on storage facilities (by type), connections, customers, and cross connection and backflow controls. It provides information on pipe age, but not about materials. It does not include information on appurtenances.

EPA's Drinking Water Infrastructure Needs Survey collects data on funding needs that include replacement of distribution infrastructure, but it does not inventory the actual infrastructure in place or its condition (EPA, 2001a). EPA has also conducted a study on modeling the costs of infrastructure (2001c) in support of the Needs Survey.

EPA's 2002 Clean Water and Drinking Water Infrastructure Funding Gap Analysis (EPA, 2002b) makes national projections of pipe replacement investment needs derived from estimated pipe age profiles in 20 cities developed by AWWA (Cromwell, 2001a). It concludes that most of the funding need for pipe replacement lies beyond the 20-year horizon of the study, with needs ramping up continually through a projected peak in 2040.

The General Accounting Office and Congressional Budget Office also conduct studies of distribution system issues from time to time, but they normally do not conduct original surveys (GAO, 1980, 2001; CBO, 2002). These studies rely on data available from other sources and on limited surveys to develop policy recommendations with budgetary implications for the federal government. They have broadly concurred that investment needs for replacement investment are growing and will present a large need.

4.1 EPA Community Water System Survey (EPA, 2002a)

The Community Water System Survey (CWSS) is a broad profile survey of the industry that has been replicated by EPA in 1976, 1982, 1986, 1995, and 2000. The most recent replications introduced a carefully designed stratified sampling design intended to represent the diversity of systems types and sizes. The 1,806 systems included in the 2000 survey sample represent a census of systems serving more tan 100,000 population. The response rates ranged from 56 to 63% for system serving more than 3,300 persons. EPA performed field visits to boost response rates to the 85 to 99% range in systems size categories serving fewer than 3,300 persons. EPA also applied a QA protocol to review of the 1,246 survey responses.

The 2000 CWSS results show that, overall, 47% of all capital expenditures is devoted to distribution and transmission infrastructure, a proportion that is fairly consistent across system size categories. The overall proportion of capital expenditures for storage facilities is 12%, which tends to be higher – up to 20% – of total outlays in small systems.

Data on pipe age shows 78% is less than 40 years old; 18% is 40 to 80 years old; and only 4% is more than 80 years old. As shown in Table 14, the age profile of pipe assets documented in the 2000 CWSS is markedly different by system size, with large systems being generally older than small systems. This is consistent with the fact that roughly half of all small systems are suburban systems that are necessarily younger than the urban areas they adjoin. Overall replacement rates are less than 1% per year, varying from 0% to almost 2%, from small to large systems.

Table 14. EPA 2000 Community Water System Survey Data on Pipe Assets

System size (pop served)	Percent of pipe per system by age class (yrs)			Average miles of pipe per system by diameter (inches)		
	< 40	40 - 80	> 80	< 6	6 – 10	> 10
< 100	90.6	9.4	0.1	1.1	0.1	0
101-500	88.3	11.7	0.1	3.4	0.5	0.1
501-3300	85.7	13.3	1	23.9	3.0	0.7
3300-10,000	84.3	12.9	2.8	60.8	18.0	4.5
10-50,000	81.4	15.3	3.4	121.4	78.0	31.1
50-100,000	70.2	23.4	6.4	141.6	121.6	78.7
100,000-500,000	60.9	29.7	9.4	259.9	181.8	139.5
500,000 +	56.3	34.4	9.2	819.0	915.7	684.0
Overall	78.0	18.0	4.0			

The 2000 CWSS provides data for each system size category on the total miles of pipe in place by diameter. As shown in Table 14, mains greater than 10-inches in diameter exist mainly in larger systems. Systems serving fewer than 3,300 persons typically have less than 1-mile of such pipe. In addition, the CWSS has data on the number of service connections in each system size category, enabling estimates of the total number of service lines in place nationally, by extrapolation. This combination of factors should also enable a good basis for developing miles of pipe/connection relationships by system size that could be used for extrapolation to estimate national totals for pipe assets by diameter and age. Since the CWSS also documents the number of storage facilities and their capacities, extrapolation to national totals for storage tanks should also be possible.

The 2000 CWSS also contains details about the presence of cross connection and backflow controls. It clearly documents a lesser degree of penetration of such practices in small systems.

4.2 EPA Drinking Water Infrastructure Needs Survey (EPA, 2005)

The EPA Needs Survey has been replicated in 1995, 1999, and 2003 to serve as the basis for reports to Congress documenting the extent of investment requirements in support of the State Revolving Loan Fund program. The survey is conducted with the assistance of state governments who have a stake in assuring a high response rate in order to substantiate the need for their share of SRF funds. The 2003 survey was conducted as a census for 1,342 systems serving more than 40,000 persons and as a random sampling of 2,553 systems serving between 3,300 and 40,000 people. For systems serving fewer than 3,300, the 2003 needs estimates were developed by extrapolation from the 1999 results that were based on a sample of 599 systems for which needs were documented by field visits conducted by EPA.

The analytical objective of the Needs Survey is to document projected capital investment needs over a 20-year horizon based on site-specific information provided by respondents to document planned investment projects. The data is subjected to QA protocols at both the state and EPA levels. Because specific projects are less formulated when they are farther off in time, the earlier versions of the Needs Survey were suspected to have understated the total needs by missing some longer term needs. The 2003 survey was implemented with extra measures to enhance the articulation of long-term needs. The result was an estimated total 20-year need of $277 billion, 60% more than the previous estimates of $167 billion. EPA concluded the increase is attributable to longer-term projects. The system size breakdown of the $277 billion total is as follows: $123 billion for large systems (> 50,000 people); $103 billion for medium size systems; and $34 billion for small systems (< 3,300 people). The order of magnitude of the 2003 total needs estimate is consistent with other major national estimates of investment needs.

Of the total estimated need of $277 billion, $184 billion is estimated to be required for transmission and distribution projects and $25 billion is identified for storage projects. Table 15 presents the breakdown of these projected needs by system size.

Table 15. EPA needs survey data on distribution, transmission and storage needs

System size (pop served)	Source & treatment needs	Distribution & transmission needs	Storage needs	Other needs	Total needs ($ 2003)
Large systems (>50,000)	24,807.1	89,779.9	6,994.5	1,270.2	122,851.7
Medium systems (3,300-50,000)	19,299.0	73,454.4	9,473.3	790.9	103,017.6
Small systems (< 3,300)	9,035.1	18,624.3	6,263.8	248.3	34,171.5
All community systems	53,141.2	181,858.6	22,731.6	2309.4	260,040.8

4.3 EPA White Papers on Distribution Systems

As mentioned earlier, a white paper that was prepared for EPA offered a summary of distribution system infrastructure issues facing the nation (American Water Works Service Co., Inc., 2002). Eight other white papers were prepared to address issues about distribution systems and are listed in this section because they may contain information that will help the reader understand infrastructure-related distribution system issues.

The paper on infrastructure covers the problems of aging and corrosion (American Water Works Service Company, 2002). It discusses general issues, such as the current condition of buried infrastructure, capital needs, technical issues of buried infrastructure, and assessment methods.

Several of the papers discuss how infrastructure failures can open paths to contamination. One paper covers how installation and repair of water mains might introduce possible routes to contamination (AWWA and Economic and Engineering Services Inc., 2002a), and another covers the potential health implications of failures at covered storage facilities (AWWA and Economic and Engineering Services Inc., 2002b). A paper on intrusion explains the possible roles of pressure transients, or specialized backflow situations, in contaminating water mains (LeChavallier, Gullick, and Karim, 2002). Another paper, on cross-connection control, explains backflow and cross-connection risks (EPA Office of Ground Water and Drinking Water, 2002). A paper on permeation and leaching is about external threats to pipes, or how chemicals can penetrate plastic pipes (AWWA and Economic and Engineering Services Inc., 2002c).

Three papers focus on water quality issues. One explains decay of water quality over time in distribution systems (AWWA and Economic and Engineering Services Inc., 2002d). Another paper discusses microbes associated with biofilms, diseases, pathogen routes to the DS, and management indicators (EPA, 2002). A third paper (AWWA and Economic and Engineering Services Inc., 2002e) explains nitrification and especially the associated health risks. Nitrification is explained as a microbial process that mainly involves oxidation of ammonia to nitrite and nitrate.

5.0 Condition Assessment of Water Distribution Pipes

Effective assessment of pipe condition is required to plan renewal programs for water distribution systems. This section of the paper describes utility condition assessment practices as observed in an industry survey, workshops, case studies and various publications. It also summarizes issues faced by utilities in implementing condition assessment.

In March 2002, WERF convened a workshop to define research priorities in asset management (WERF, 2002). The top-ranked research need arose from the lack of standardized guidelines for conducting condition assessments and using such data to understand asset condition and performance. AwwaRF and WERF have a joint project ongoing to address fill this gap (Urquhart, 2004).

The context for understanding the objective of condition assessment is anchored in principles that have been established in the global best practice of asset management, as documented by utility practitioners in Australia and New Zealand in the International Infrastructure Management Manual (NAMS, 2006). The objective of asset condition and performance assessment is not to manage asset condition, but to manage failure risk (Urquhart, 2005). The purpose of condition data is to make an assessment of the remaining life of the asset so that rehabilitation or replacement investment can be planned and implemented before failures occur that would cost the utility more than it would to have avoided such failures through asset management. This risk management context provides the basis on which the cost of condition assessment is justified. In the standard practice of asset management, there is an important risk prioritization step in which a differentiation can be made between "reactive" assets and "proactive" assets (Urquhart, 2004). It is worth noting that the best practice in applying this risk management protocol takes full account of the environmental and social costs of failures in applying the risk management discipline in a triple bottom line sense.

Reactive assets are those for which the consequences of failure are quite low. Main breaks on small lines on residential streets would be an example. Given the cost of condition assessment on small lines and the difficulty of predicting specific failures on a hundred miles or more of individual small lines, it is much more cost-effective to simply fix lines when they break. Some Australian utilities have in fact focused their entire small mains asset management program on that objective by focusing on responsiveness to failure as the best risk management approach — reducing the cost per break repair and the time-out-of-water (Cromwell, 2001b). Condition data is useful in planning rehabilitation and replacement investments for small mains, but these reactive assets are approached as a population of assets, using statistical analysis of pooled data on such parameter as break trends segmented by pipe material and soil type in order to assess overall replacement needs. This type of statistical analysis of aggregate performance data, such as breaks, does not cost as much as some other forms of actual condition assessment of specific lines and is therefore more suitable to lower priority risks.

Typical data used for such analysis includes pipe age, pipe material, pipe diameter, soil conditions, number of breaks, any rehabilitation that might have been conducted on the pipe, pressure of operation, and complaints of taste, odor, color, or low pressure associated with the delivered water. However, the lack of standardized procedures and common terminology for recording data on leaks and breaks has challenged adoption of such programs. For instance, some utilities do not differentiate by pipe failure type, yet the mode of failure can provide insight on the condition of the pipe. It is often assumed that the mode of failure is corrosion failure. While this is an important type of failure, there are a variety of factors that contribute to failure (pipe break). As another example, many northern climate pipe failures occur in the fall and spring, as soil temperatures are either decreasing with the advent of winter, or increasing with spring. These pipe failures tend to be circumferential failures typically due to soil movement, and have little or nothing to do with corrosion. Other types of failures, when properly identified and analyzed, can also yield useful condition information

New factors to consider within this risk management framework have recently come to light and will have to be incorporated. First, there is growing evidence that pipes very often leak before they break. Further, it may be the case that some breaks would not even occur if the leaks had been fixed when they first began, preventing them from potentially undermining pipe foundations and producing stresses where there were none (Hughes, 2002). This suggests that leak detection could become a much more significant tool for proactive efforts, even applied to small mains.

A second major area of concern involves not just the physical condition of pipes (especially small mains), but also their water quality performance. Performance failure is just as important as physical failure. With tightening regulatory requirements on water quality at the tap and the potential disruption of the chemical and biological equilibrium in old pipes when subjected to different waters produced by advanced treatment processes, the useful life of some pipes may be shortened if stable performance in terms of delivered water quality cannot be recovered. Thus, water quality monitoring must be regarded as an essential component of asset condition assessment. In addition to these concerns, there is also growing concern that repeated main breaks in small lines may be an important source of contamination threats. This could have the effect of either increasing the cost of main repairs or decreasing the number of failures that should be endured prior to replacement. The effect is the same – shorter pipe life.

"Proactive" assets are those for which the consequences of failure are quite high, making it worthwhile to be proactive about managing failure risk. An example would be the loss of a large main lying under Main Street, causing significant damage and disruption in addition to substantial service outage. Because so much is at stake, the cost entailed in conducting and evaluating condition assessment data is more than justified for such "proactive" assets that are also called "critical assets" in the parlance of vulnerability assessments recently conducted in the US.

At this time the accepted method of recording results of condition assessments for 'proactive" assets (or, critical assets) is a five-point scoring system, such as the following (Morrison, 2005):

1. Little or no deterioration, performance more than adequate.
2. Minor deterioration, performance adequate.
3. Mildly deteriorated, short-term performance just adequate, however will require renewal or replacement soon.
4. Severely deteriorated and in need of repair, renewal or replacement.
5. In danger of immediate failure, requires emergency repair or replacement.

Non-destructive inspection is commonly done in wastewater lines using closed-circuit television (CCTV) cameras. This technology has provided valuable information to wastewater managers and the five point scoring system has actually been put to use for wastewater mains using such data. However, the application of CCTV is much less valuable in the potable water environment where failure modes are different, access to these pressurized systems is much more limited, and pipes are usually smaller. The unique nature of pressurized water distribution system presents a significant technical challenge for universal scoring protocols. This requires adaptable tools and training to address the myriad pipe sizes, materials, and ages, as well as fittings with tight bends and other constrictions. Advanced applications will be required for the future, which may include real–time assessment, smart pigs, automated pipe data registration and other technologies.

Most non-destructive inspection technologies require some type of hardware access to the interior of the pipe, and for the pipe to be dewatered for effective inspection. The requirement for access to the interior of the pipe can result in high first-time inspection costs because water systems may need to modify their system. For instance, a major US city recently spent approximately $700,000 for inspection of one mile of 36-inch diameter pipe. Most of this cost was associated with gaining access to the interior of the pipe. Approximately 17% of the cost was the actual inspection. The dewatering requirement, traffic control, inspection manhole installations, and pavement restoration in an urban environment can result in high indirect costs, and also severely limit the timeframes when inspection is feasible. The overall cost of nondestructive inspection at this time limits the economic application of these technologies to larger diameter pipe (typically 24-inches or greater in the US). The failure of large pipes in this size range is a rare event, but typically creates significant direct damage and service outage issues and thus makes the associated cost justifiable — if the utility recognizes the inherent risk management context of asset management.

One of the greatest success stories of non-destructive testing in the potable water sector has resulted from a number of catastrophic failures of large diameter PCCP due to failure of metal reinforcing bands. Ingenious use of magnetic, acoustic and fiber optic technologies have produced a substantial toolkit for utilities facing this risk (Johnson and Shenkiryk, 2006), demonstrating that perhaps technology can rise to the challenge in this area.

Additional research has been called for during the past decade (Kleiner, 2005) to include nondestructive test methods for determining the condition of existing pipe, improved leak detection equipment and methods to measure losses, studies of causes for pipe, joint, lining, and coating deterioration, including corrosion, and development of better in-situ methods to test condition. Taking into account the evolution of research and trends in the water supply industry, it seems likely that in the future utilities will more actively manage distribution systems with more monitors, safeguards, and protective systems. For instance, recent work on water accounting has developed a defined set of terms and a considerably increased understanding of water leakage. Partly due to these developments work is now ongoing to improve real-time pressure management, which is directly related to leakage, and leak detection hardware. While this is just one example, it is representative of a general trend.

Both technologies and methods are evolving to improve condition assessment capabilities. This conclusion is based on a recent synthesis of AwwaRF reports on distribution system infrastructure. AwwaRF has commissioned a number of recent studies on distribution system infrastructure, and experts recommended more and continued research on failure mechanisms with different types of pipe, causes for pipe, joint, lining, and coating deterioration, and continuing integration of results, along with more focused and practical guidance for utilities in this complex arena. In general, the goal is to develop more accurate, user-friendly test methods to determine condition of pipe, to expand understanding of causes for deterioration, leaks, and breaks, and to prevent problems and predict length of life under various conditions.

6.0 Conclusions

The paper summarized the available data on the inventory and condition of the nation's water distribution infrastructure. Taken together, the available data and companion studies provide much more information on distribution systems than existed even as recently as a decade ago. EPA has conducted a number of studies about distribution systems, including surveys and research investigations, and more detailed data is available in AWWA's Water://Stats program. AWWA and AwwaRF have also conducted a number of separate studies, both relying on existing data and on surveys and/or case studies.

At the national level, the database of inventory information on distribution systems is fairly good. However, the national database is built from utility-level information that has not in all cases been verified. While some data on age of constructed facilities is available, data on condition of systems is weak.

The paper reported on data contained in the literature and distribution system data from AWWA's 2002 Water://Stats survey, which is the latest available. The matrix of data availability shows that data on pipes, finished water storage, hydrants, some types of valves, and customer service lines is generally good. Very little data is available on other components of distribution systems.

National data from EPA surveys and the AWWA Water://Stats surveys can be disaggregated to provide regional and/or system size categorical data. Trends can be analyzed for regions or system sizes, and by comparisons with previous surveys, time trends can be evaluated.

From recent research, the water industry has a good understanding of how condition assessment is practiced by utilities. Condition assessment is not done consistently by utilities, and system condition is not well known by most utilities. Gross indicators such as "poor" or "good" condition are normally reported, rather than remaining life and more definite indicators. The art and science of condition assessment need further improvements. While tools for condition assessment hold promise, more development and training are necessary to advance the state of knowledge.

7.0 References

American Water Works Service Co., Inc. 2002. Deteriorating Buried Infrastructure Management Challenges and Strategies. Issue Paper for EPA. http://www.epa.gov/safewater/tcr/tcr.html#distribution. Accessed February 13, 2004.

AWWA and Economic and Engineering Services Inc. 2002a. New or Repaired Water Mains. Distribution System Issue Paper. http://www.epa.gov/safewater/tcr/tcr.html#distribution. Accessed February 17, 2004.

AWWA and Economic and Engineering Services Inc. 2002b. Finished Water Storage Facilities. Distribution System Issue Paper. http://www.epa.gov/safewater/tcr/tcr.html#distribution. Accessed February 17, 2004.

AWWA and Economic and Engineering Services Inc. 2002c. Permeation and Leaching. Distribution System Issue Paper. http://www.epa.gov/safewater/tcr/tcr.html#distribution. Accessed February 17, 2004.

AWWA and Economic and Engineering Services Inc. 2002d. Decay in Water Quality Over Time. Distribution System Issue Paper. http://www.epa.gov/safewater/tcr/tcr.html#distribution. Accessed February 17, 2004.

AWWA and Economic and Engineering Services Inc. 2002e. Nitrification. Distribution System Issue Paper. http://www.epa.gov/safewater/tcr/tcr.html#distribution. Accessed February 17, 2004.

AWWA. 2004. Water://Stats 2002 Distribution Survey. Denver, CO: AWWA.

Congressional Budget Office (CBO). 2002. Future Investment in Drinking Water and Wastewater Infrastructure.

Cromwell, J., E. Speranza, and H. Reynolds. 2001a Reinvesting in Drinking Water Infrastructure: Dawn of the Replacement Era. Denver, CO: AWWA.

Cromwell, J., G. Nestel, R. Albani, L. Paralez, A. Deb, and F. Grablutz. 2001b. Financial and Economic Optimization of Water Main Replacement Programs. Denver, CO: AWWA Research Foundation.

Cromwell, J.E. III, R.G. Lee, and E. Kawczynski. 1990. Development of the AWWA Water Industry Data Base: A "Facts" Machine for the Future. Cincinnati, OH: AWWA Annual Convention.

Deb, A.K., Y.J. Hasit, H.M. Schoser, and J.K. Snyder. 2002a. Decision Support System for Distribution System Piping Renewal. Denver, CO: AWWA Research Foundation: Distribution Systems.

Deb, A.K., F.M. Grablutz, Y.J. Hasit, J.K. Snyder, G.V. Loganathan, and N. Agbenowski. 2002b. Prioritizing Water Main Replacement and Rehabilitation. Denver, CO: AWWA Research Foundation.

Deb, A.K., K.A. Momberger, Y.J. Hasit, and F.M. Grablutz. 2000. Guidance for Management of Distribution System Operation and Maintenance. Denver, CO: AWWA Research Foundation: Distribution Systems.

Deb, A.K., Y.J. Hasit, F.M. Grablutz, and R.K. Herz. 1998. Quantifying Future Rehabilitation and Replacement Needs of Water Mains. Denver, CO: AWWA Research Foundation: Distribution Systems.

Deb, A.K., Y.J. Hasit, and F.M. Grablutz. 1995. Distribution System Performance Evaluation. Denver, CO: AWWA Research Foundation: Distribution Systems.

Deb, A.K., Y.K. Hasit, and F.M. Grablutz. 1995. *Distribution System Performance Evaluation*. Denver, CO: AWWA Research Foundation: Distribution Systems.

Deb, A.K., Y.J. Hasit, J.A. Williams Jr., and R. Jacob. 2001. New Techniques for Precisely Locating Buried Infrastructure. Denver, CO: Awwa Research Foundation.

Environmental Protection Agency. 2004. Issue Papers. http://www.epa.gov/safewater/tcr/tcr.html#distribution. Accessed January 26, 2004.

Environmental Protection Agency. 2002a. *Community Water Systems Survey – 2000*. 815-R-02-005A,B. December. http://www.epa.gov/safewater/consumer/cwss_2000_volume_i.pdf. Accessed January 27, 2004.

Environmental Protection Agency. 2002b. Health Risks from Microbial Growth and Biofilms in Drinking Water Distribution Systems Distribution System Issue Paper. http://www.epa.gov/safewater/tcr/tcr.html#distribution. Accessed February 17, 2004. (Authorship of paper is not noted).

Environmental Protection Agency. 2002c. *The Clean Water and Drinking Water Infrastructure Gap Analysis*. 816-R-02-020. September.

Environmental Protection Agency (Office of Ground Water and Drinking Water). 2002d. Potential Contamination Due to Cross-Connections and Backflow and the Associated Health Risks. Distribution System Issue Paper. http://www.epa.gov/safewater/tcr/tcr.html#distribution. Accessed February 17, 2004.

Environmental Protection Agency. 2005. *Drinking Water Infrastructure Needs Survey*. Third Report to Congress. EPA 816-R-05-001. Washington, DC: U.S. Environmental Protection Agency.

Environmental Protection Agency. 2006. *2003 Drinking Water Infrastructure Needs Survey: Modeling the Cost of Infrastructure*. EPA 816-R-06-007. Washington, DC: U.S. Environmental Protection Agency.

Government Accountability Office (GAO). 2001. Report on Water Infrastructure: Information on Federal and State Financial Assistance.

Government Accountability Office (GAO). 1980. Comptroller General of the United States. November 24, 1980. Additional Federal Aid for Urban Water Distribution Systems Should Wait Until Needs Are Clearly Established. CED-81-17.

Grigg, N.S. 2004. Assessment and Renewal of Water Distribution Systems. AwwaRF Report Number 91025. Denver, CO.

Grigg, N.S. 1988. Water Utility Operating Data, 1984. American Water Works Association.

Hughes, D. et al. 2002. Assessing the Future: Water Utility Infrastructure Management. Denver, CO: AWWA.

Johnson, B. and M. Shenkiryk. 2006. Condition Based Asset Management for Critical Water Pipelines. Underground Infrastructure Management, May/June 2006.

Keeley, K. 2003. AWWA Survey of Operating Data, 1945-1985. Unpublished document. Denver, CO: AWWA.

Kirmeyer, G.J., W. Richards, and C.D. Smith. 1994. An Assessment of Water Distribution Systems and Associated Research Needs. Denver, CO: AWWA Research Foundation: Distribution Systems.

Kleiner, Y. et al. 2005. Risk Management of Large Diameter Water Transmission Mains. Denver, CO: AwwaRF.

LeChavallier, M.W., R.W. Gullick, and M. Karim. 2002. The Potential for Health Risks from Intrusion of Contaminants into the Distribution System from Pressure Transients. Distribution System White Paper. http://www.epa.gov/safewater/tcr/tcr.html#distribution. Accessed February 17, 2004.

Morrison, R. 2004. Condition Assessment – Back to Basics. Underground Infrastructure Management. November/December.

NAMS (National Asset Management Steering Group). 2006. International Infrastructure Management Manual. New Zealand.

National Research Council. 2006. Drinking Water Distribution Systems: Assessing and Reducing Risks. Committee on Public Water Supply Distribution Systems. Washington, DC.

O'Day, D.K., R. Weiss, S. Chiavari, and D. Blair. 1986. Water Main Evaluation for Rehabilitation/Replacement. Denver, CO: AWWA Research Foundation and Environmental Protection Agency.

Seidel, H.F. 1985. Water Utility Operating Data: An Analysis. *Journal of American Water Works Association* Vol. 77, No. 5, p 34-41, May.

Smith, L.A., K.A. Fields, A.S.C. Chen, and A.N. Tafuri. 2000. *Options for Leak and Break Detection and Repair of Drinking Water Systems*. Columbus, OH: Battelle Press.

Stratus Consulting. 1998. Infrastructure Needs for the Public Water Supply Sector. Report for American Water Works Association. Boulder, CO. December.

Urquhart. A. 2005. Incorporating Condition Assessment into a Comprehensive Asset Management Program. Underground Infrastructure Management. November/December.

Urquhart, A. 2004. Protocols for Assessing Condition and Performance of Water and Wastewater Assets. Denver, CO: AwwaRF.

WERF. 2002. Research Priorities for Successful Asset Management: A Workshop. Alexandria, VA.