# APPENDIX K

# DRINKING WATER AND SEWER SYSTEMS

External corrosion on ductile iron pipe

Two clamps on water main

Water main break

Water treatment plant

Pit in copper tubing

Erosion-corrosion of copper water pipe

Stray current corrosion

## *APPENDIX K*

# DRINKING WATER AND SEWER SYSTEMS

**MICHIEL P.H. BRONGERS**[1]

## SUMMARY AND ANALYSIS OF RESULTS

### Corrosion Control and Prevention

Americans consume approximately 550 L of drinking water per person per day, for a total annual quantity of approximately 56.7 billion $m^3$. The treated drinking water is transported through 1.4 million km of municipal water pipes. The water pipes are subject to internal and external corrosion, resulting in pipe leaks and water main breaks.

The total cost of corrosion for the drinking water and sewer systems includes the cost of replacing aging infrastructure, the cost of unaccounted-for water, the cost of corrosion inhibitors, the cost of internal cement mortar linings, the cost of external coatings, and the cost of cathodic protection.

In March 2000, the Water Infrastructure Network (WIN) estimated the current annual cost for new investments, maintenance, operation, and financing of the national drinking water system at $38.5 billion per year, and that of the sewer system at $27.5 billion per year. The total cost of corrosion was estimated from these numbers by assuming that at least 50 percent of the maintenance and operation costs are to replace aging (corrosion) infrastructure, while the other 50 percent would be for system expansion. This results in an estimated cost of corrosion for drinking water systems of $19.25 billion per year and for sewer systems of $13.75 billion per year.

WIN stated that the current spending levels are insufficient to prevent large failure rates in the next 20 years. The WIN report was presented in response to a 1998 study by the American Water Works Association (AWWA) and a 1997 study by the U.S. Environmental Protection Agency (EPA). Those studies had already identified the need for major investments to maintain the aging water infrastructure.

In addition to the costs of replacing aging infrastructure, there is the cost of unaccounted-for water. One city reported a constant percentage of unaccounted-for water of 20 percent in the last 25 years, with 89 percent of its main breaks directly related to corrosion. Nationally, it is estimated that approximately 15 percent of the treated water is lost. The treatment of water that never reaches the consumer results in inflated prices (national lost water is estimated at $3.0 billion per year) and over-capacity in treatment facilities.

Adding these three major cost items results in a total annual cost of corrosion of $36.0 billion per year for drinking water and sewer systems combined.

### Opportunities for Improvement and Barriers to Progress

Water transmission and distribution systems can be protected from internal corrosion by using corrosion inhibitors in combination with pH adjusters and alkalinity control. A second method of internal corrosion protection is the application of a cement mortar lining to iron-base pipes. External corrosion protection can be obtained from coatings and cathodic protection.

---

[1] CC Technologies Laboratories, Inc., Dublin, Ohio.

The cost of corrosion inhibitors added to the drinking water is a percentage of the total treated water cost. AWWA estimated that the annual costs for corrosion inhibitor treatment ranges from $1.00 to $1.50 per residential consumer. With approximately 66 million residential customers, the total cost can be estimated at $82 million per year, which is 2.5 percent of the total annual treated water cost.

New iron and steel pipelines are commonly lined with cement mortar. Cement mortar linings are also used for rehabilitation of older ductile iron, cast iron, and steel water pipeline networks. The linings can eliminate small leaks in pipes and pipe connections as a result of the high resistance of cement mortar to pressure, enhance the hydraulic characteristics of the mains, and prevent further internal corrosion damage. Studies by AWWA show that the cost for water pipe rehabilitation by cement mortar lining ranges from 13 percent to 41 percent of the costs of total pipe replacement.

Several studies show that the direct cost of maintenance and repair of water pipes, and repaving after work is done is approximately 50 percent of the total budget of water departments. Repairs can be prevented if control methods are applied to the system. External corrosion can be effectively mitigated by the application of coatings and cathodic protection. Although these systems have problems of their own, the initial cost for installing coatings and cathodic protection on new systems is almost always warranted because large maintenance cost-savings can be achieved over the life of the piping system.

A major barrier to progress in corrosion management is the absence of complete and up-to-date information on all water systems. Limited communication between water utilities limits the awareness and implementation of available corrosion control technologies, such as new coating systems and cathodic protection. In addition, the lack of information complicates the process of prioritizing maintenance. AWWA maintains partial records on the water systems of its members, and the U.S. EPA collects data from voluntary questionnaires; however, most water utilities do not have complete records on all of their buried pipes. The pipe mileage length, pipe materials, pipe diameters, and their installation dates are, in many cases, unknown. At the local level, corrosion engineers maintain small databases with information on the nature of individual repairs, but often these records are not integrated in a larger data system. Computers provide the opportunity to maintain the records both in local and national databases.

A second barrier to progress in corrosion management is the lack of understanding and awareness of corrosion problems at the local level, and the limited time dedicated to solving corrosion problems. Often, an attitude is taken of burying the water pipe and forgetting about it until it fails. Investigations of corrosion-related parameters in drinking water are an important aid to water utilities. The data should be used to regularly re-evaluate the applied chemical treatment for internal corrosion protection. External corrosion protection can be evaluated by systematic inspection of coatings and inspection of the cathodic protection systems at regular intervals.

New developments in electronic equipment make internal inspection with cameras an option to evaluate the condition of pipe sections. These techniques, however, are not commonly used because they are still quite expensive, the equipment insertion into and extraction from the pipe is usually difficult, and the pipe may have internal obstructions or bends. In addition, analysis of the data is generally time-consuming and diffucult.

## Recommendations and Implementation Strategy

It is recommended that a national effort be initiated in order to decrease the total amount of unaccounted-for water using several available methods. The objective of this effort would be to prevent increasing consumer prices and to more effectively use the capacity of treatment facilities. Furthermore, a decrease in unaccounted-for water will also decrease the total quantity of chemicals used to treat drinking water.

It is recommended that a national resource expertise be created where water utilities can get information about corrosion, where agencies can receive support to develop their corrosion protection plan, and where corrosion awareness training for employees is provided.

It is recommended that a national database be created to which all water utilities must submit complete records on changes to their systems. This will enable water utility managers to better understand the reasons for system growth, to accurately estimate pipe replacement rates, and to prioritize funding for corrosion maintenance and aging system rehabilitation.

Finally, it is recommended that regularly scheduled corrosion inspections be conducted on water treatment facilities, water tanks and towers, and water transmission and distribution systems. The inspections should evaluate the effectiveness of internal and external corrosion protection measures so that the integrity of the aging infrastructure is maintained at the lowest possible cost.

## Summary of Issues

| | |
|---|---|
| Increase consciousness of corrosion costs and potential savings. | The total cost of corrosion for drinking water and sewage systems is $36.0 billion/year. This cost is divided in $19.75 billion for drinking water systems, $ 13.25 billion for sewage water systems, and $3.0 billion in consumer costs for unaccounted-for water. The cost for added corrosion inhibitors is only a small part of the total cost: $82.5 million/year. |
| Change perception that nothing can be done about corrosion. | Internal corrosion can often be prevented or slowed down if corrosion inhibitors are used in combination with a system of internal linings and coatings. External corrosion can be prevented and slowed down with the use of external coatings and the application of cathodic protection. In a case study reported by AWWA, it was reported that the costs for water pipe rehabilitation by cement mortar linings can be very economical compared with total pipe replacement. The costs of mortar linings ranged from 13 percent to 41 percent of the costs of total pipe replacement. |
| Advance design practices for better corrosion management. | Corrosion engineering will be more effective if training about corrosion is provided to maintenance personnel and water system designers. They will recognize corrosion problems in the design and after the system is in service. Also, they will be aware of the latest developments in corrosion technology, including inhibitors, coatings, and cathodic protection. In the last 25 years, major advances have been made in the development of new coating systems and corrosion inhibitors. |
| Change technical practices to realize corrosion cost-savings. | In many cases, no corrosion protection is applied, and the only corrosion allowance is in the wall thickness of the water system. The application of internal coatings and linings, corrosion inhibitors, external coatings, and cathodic protection have great potential to realize corrosion cost-savings. It is noted that the selection of the corrosion protection system is always related to the specific site and application. |
| Change policies and management practices to realize corrosion cost-savings. | It was found that most utilities maintain detailed information about their local system. However, nationally, the system information is not coupled. A complete and up-to-date national water system database could include data on unaccounted-for water and improve communication between departments and between individual utilities. In addition, corrosion knowledge could be more easily compared if coupled information would be available in a generally used format, and the assessment of the effectiveness of different corrosion control approaches could be improved. |
| Advance life prediction and performance assessment methods. | Currently, estimates for pipe replacement rates range from as low as 0.46 percent to as high as 5.0 percent. Utilities should gather relevant data to determine the pipe replacement rate, because it helps in the planning and budgeting for system maintenance. Improved modeling of pipe replacement would allow statistical analysis and predictive assessments for the performance of the system. |

| | |
|---|---|
| Advance technology (research, development, and implementation). | Most utilities do not have a proactive inspection plan to find leaks in their water pipes. Often, leaks are only repaired if they are so large that the water pressure drops significantly or if a flood occurs. This results in many leaks that go undetected for a long time and large losses of treated water. The development and implementation of technologies to detect leaks has the potential of large cost-savings. These techniques could include pressurization tests and internal inspection procedures. For internal inspection, the pipes need to be made accessible for the internal inspection tools. |
| Improve education and training for corrosion control. | Training should be provided to maintenance personnel so that they will identify corrosion problems in the field. Present corrosion protection techniques should be made accessible to field crews. |

## TABLE OF CONTENTS

## TABLE OF CONTENTS (continued)

## LIST OF FIGURES

# LIST OF TABLES

# SECTOR DESCRIPTION

Communities in the United States have always provided water to individuals and businesses using groundwater and surface water sources. The water infrastructure is divided into two separate and complementary systems: drinking water services and waste water services. These services consist of a continuously changing and expanding system of water sources, water storage, transmission piping, distribution piping, and treatment facilities. The water system consists of a range of materials in contact with water and soils that vary in quality, both temporally and from one part of the system to another. The utilities operating the individual systems provide water according to the quality standards set forth in the 1996 Safe Drinking Water Act (SDWA) amendments.(1)

Americans use a lot of water. Annually, about 56.7 billion $m^3$ (15 trillion gal) of drinking water serves approximately 66 million customers in the United States, with the average total water use rate per customer ranging between 473 and 662 L/capita/day [125 and 175 gal/capita/day (gpcd)]. Recent benchmark estimates by the American Water Works Association (AWWA) on indoor water use rates, indicated an average use rate of 245 L/capita/day (64.6 gpcd).(2) The average consumer cost for clean water ranges from \$0.50 to \$2.50 per 3.78 $m^3$ (1,000 gal). Corrosion inhibitors are chemicals that are dosed in small quantities and that provide a significant reduction in corrosion. Corrosion inhibitors cost approximately \$5.29 per million L (\$20 per million gal). The cost for corrosion inhibitors in water treatment is a very small percentage of the treated water cost.

The sewer system is approximately the same size as the drinking water system. The 1995 U.S. Geological Survey Circular(3) reported that approximately 16,400 publicly owned treatment facilities released some 155 million $m^3$ (41 billion gal) per day of treated wastewater nationwide during 1995.

Over the years, small systems have been combined to form larger systems for the economic benefits of scale. Large systems were interconnected to accommodate temporary demand in certain areas by transporting water from other areas. In the process of maintaining, replacing, upgrading, and combining water systems, many different construction materials and methods have been used. The current extensive and complex water system is a one-of-a-kind result of more than a hundred years of water system engineering. Therefore, maintenance of the existing structures for continued supply and the design and installation of new structures for system expansion pose major technical challenges.

Based on the AWWA Water Industry Database (WIDB),(4) Staples(5) reported in 1995 that the entire United States had approximately 1.4 million km (0.88 million mi) of municipal water piping. Table 1 shows an estimated profile of the different materials that make up these water pipes. (Similar information for wastewater systems was not found.) In 1998, the AWWA Research Foundation used the same database to estimate the total mileage at 0.97 million km (approximately 0.61 million mi), which is only 70 percent of the previous value. Staples estimated that new pipes are being installed at a rate which extend the system length by 1.5 percent per year, while an additional 0.5 percent is being replaced annually.

Table 1. Profile of different materials used for U.S. transmission water pipes, as determined from the 1992 AWWA water industry database.(4-5)

| MATERIAL | PERCENTAGE |
|---|---|
| Cast Iron | 48 |
| Ductile Iron | 19 |
| Concrete and Asbestos Concrete | 17 |
| PVC | 9 |
| Steel | 4 |
| Other | 2 |
| **TOTAL** | **99%** |

In the current research, it was found that most water utilities do not have complete records of all their buried pipes. The pipe mileage length, materials, and diameters, as well as installation dates, are in many cases, unknown. In many cases, this information is missing due to the age of the system and the change of organizations over the years. The lack of complete up-to-date information about all water systems complicates the process of prioritizing maintenance and the assessments for corrosion protection. The fact that computers have become commonplace in recent years provides the opportunity to maintain records in local databases and in a national database.

System reliability is of the utmost importance to water suppliers and their customers. Corrosion jeopardizes system reliability by causing leaks and breaks and by affecting water quality. Corrosion problems vary within a single system because many variables affect corrosion, such as pipe material, pipe age, pipe wall thickness, water additives, corrosion inhibitor treatment, soil chemistry, soil moisture content and/or local groundwater level, and stray currents.

## Corrosion Cost Estimates

Because of the deterioration of the water infrastructure, a number of recent studies were conducted. The studies addressed the current and future needs for replacement and expansion of the infrastructure. Each study had a different scope and used different methods to collect the data and to calculate the current and future infrastructure needs.

In the following sections, three studies are reviewed that estimate the cost of drinking water and wastewater infrastructure in the United States. Table 2 summarizes and compares the three reports. The first two studies deal with drinking water systems only, while the third study includes both drinking water and wastewater. The three studies are:

- EPA Drinking Water Infrastructure Needs Survey, 1997.
- AWWA Report on Drinking Water Infrastructure Needs, 1998.
- Water Infrastructure Network (WIN) Report on Clean and Safe Water for the 21st Century, 2000.

### EPA – Drinking Water Infrastructure Needs Survey – 1997

In 1997, the U.S. Environmental Protection Agency (EPA) presented the Drinking Water Infrastructure Needs Survey to Congress.(6) The objective of this study was to estimate the cost of maintenance of the U.S. drinking water system for a 20-year time period. The analysis of the data focused on the future infrastructure needs and whether these needs were due to system expansion (growth) or system deterioration (aging).

The EPA national survey estimated that the nation's 55,000 community water systems must invest a minimum of $138.4 billion (1995 dollars) over the next 20 years ($6.9 billion per year) to install a new infrastructure and upgrade or replace an existing infrastructure to ensure the provision of safe drinking water. Of this total, $12.1 billion (8.7 percent) would be needed immediately (distributed over the first few years) to meet the current SDWA requirements. All values in this study were reported in 1995 dollars. In addition, the report did not correct for financing costs as part of the anticipated capital investment costs.

In the EPA study, approximately 4,000 community water systems documented their infrastructure needs by filling out questionnaires. The questions included requests for information about currently deficient structures and future infrastructure projects. Table 3 shows the categories for investment considered in this study and the total need as determined from the questionnaires.

Table 2. 20-year water infrastructure needs in billions of dollars: Summary of the 1997 EPA report,[(6)] the 1998 AWWA report,[(8)] and 2000 WIN report.[(9)]

| | | **1997** | | **1998** | | **2000** | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | **EPA** | | **AWWA** | | **WIN** | | | |
| | | **Drinking water** | **Sewage water** | **Drinking water** | **Sewage water** | **Drinking water** | | **Sewage water** | |
| | | **NEED** | **NEED** | **NEED** | **NEED** | **NEED** | **CURRENT** | **NEED** | **CURRENT** |
| **Transmission & Distribution** | **Maintenance** | 77.2 | - | 325 | - | 27/year = 540 / 20 yrs | 23/year = 460 / 20 yrs | 27/year = 440 / 20 yrs | 15/year = 300 / 20 yrs |
| | **Operation** | - | - | - | - | | | | |
| **Water Treatment** | **Maintenance** | 36.2 | - | - | - | | | | |
| | **Operation** | - | - | - | - | | | | |
| **Water Storage** | **Maintenance** | 12.1 | - | - | - | | | | |
| | **Operation** | - | - | - | - | | | | |
| **Water Source** | **Maintenance** | 11.0 | - | - | - | | | | |
| | **Operation** | - | - | - | - | | | | |
| **Other Water Needs** | **Maintenance** | 1.9 | - | - | - | | | | |
| | **Operation** | - | - | - | - | | | | |
| **Financing*** | | - | - | - | - | 100 | 100 | 100 | 100 |
| **Capital Investments** | | - | - | - | - | 380 | 210 | 360 | 150 |
| **TOTAL** | | 138.4 (6.9 / year) | - | 325 (16.3 / year) | - | 1,020 (51 / year) | 770 (38.5 / year) | 900 (45 / year) | 550 (27.5 / year) |
| | | Billions of 1995 Dollars | | Billions of 1997 Dollars | | Billions of 2000 Dollars | | | |
| **Infrastructure Replacement Rate** | | **User Specified** | **-** | **Uniform, 0.5 – 1.5%** | **-** | **Uniform, 0.5 – 1.5%** | **-** | **5.0%** | **-** |

*Change in financing costs was not specified by WIN, and therefore the financing costs were given as constant ($100 billion / 20 years) in this table.

Table 3. Total 20-year capital investment needs by category, according to the 1997 EPA Drinking Water Needs Survey (in 1995 dollars).(6)

| CATEGORY | TOTAL NEED ($ x billion) | PERCENTAGE |
|---|---|---|
| Transmission and Distribution | 77.2 | 56 |
| Water Treatment | 36.2 | 26 |
| Water Storage | 12.1 | 9 |
| Water Source | 11.0 | 8 |
| Other | 1.9 | 1 |
| **TOTAL** | **$138.4** | **100%** |

In 2000, the EPA survey manager(7) explained that the database that served as a basis for the EPA report(6) contained details on 35,545 separate projects listed by the utilities interviewed. The project size ranged from several hundred dollars for rural systems to $699 million for the largest municipal systems. The size of the population served per system ranged from several tens to 15 million people. When the project costs were divided by the number of people served by the improvement, the costs ranged from pennies to $44,000 per person. From the 436 projects that were reported to cost more than $1,000 per person (i.e., $50 per year for 20 years), 158 projects served more than 1,000 people. Most of these relatively expensive projects included transmission and distribution line replacement or rehabilitation, while only a few of these projects were for source or treatment needs. Currently, work is underway on an updated version of the EPA Drinking Water Needs Survey.

## AWWA – Infrastructure Needs for the Public Water Supply Sector – 1998

In 1998, the American Water Work Association (AWWA) presented the *Infrastructure Needs for the Public Water Supply Sector* report.(8) The objective of this report was to provide an assessment of the capital investment needs for the water supply community over the next 20 years. This AWWA report was written as a review of the 1997 EPA report, discussed previously, and was intended to be an independent assessment of the potential magnitude of the capital investment needs for water distribution and transmission systems.

AWWA recognized the concern in the drinking water community regarding how much additional investment will be needed over the coming decades for infrastructure upgrades. These infrastructure needs encompass both what is required by the 1996 SDWA amendments, as well as what will be needed to replace and rehabilitate aging water treatment and distribution facilities, regardless of federal regulatory mandates.

In contrast to the EPA report, AWWA examined current water transmission[2] system needs and other long-term infrastructure investment requirements for U.S. water utilities. AWWA commented in their report that the EPA study was solely based on the questionnaires returned by utilities. They indicated that it was therefore possible that many of the answers were based on the Capital Improvement Project (CIP) plans of the individual water systems. The AWWA report stated that the CIP plans typically have only a 5-year timespan, and as a result, the EPA estimates may have been low.

In the AWWA analysis, the expected mileage of pipe to be replaced annually was determined from the current amount of water pipe buried in the United States, multiplied by an average annual rate of replacement, as determined from various sources. The replacement rate signifies the fraction of pipe being replaced annually and can be used to estimate the total time required to replace the entire system once.

---

[2] AWWA uses the word “distribution” pipe to refer to large-diameter underground pipe for transportation of water over long distances. In the current report, this pipe is called “transmission” pipe, while the term “distribution” is reserved for relatively small-diameter pipes in residences and businesses.

The 20-year infrastructure needs were calculated by multiplying the annual replacement rate, the total U.S. length of transmission pipe, the expected unit cost per meter of replaced pipe, and the time over which the replacement takes place (i.e., 20 years). Although the following equation appears simple, the actual calculation requires the application of ranges of data and a statistical analysis:

$$\text{20-Year Infrastructure Needs} = \text{Replacement Rate} \times \text{Kilometers} \times \text{Unit Cost} \times \text{20 years}$$

Based on the AWWA calculations, the anticipated 20-year capital needs for distribution systems of U.S. water utilities were estimated to be $325 billion (1998 dollars), or $16.3 billion per year. From the "Waterstats" database, the AWWA Research Foundation estimated in 1998 that approximately 0.89 to 1.06 million km (0.55 to 0.66 million mi) of transmission pipe are currently in service. The calculations for future spending in the drinking water infrastructure strongly depend on the estimated pipe replacement rates. The pipe replacement rate is defined as the percentage of the total length of water pipe in a system that is replaced in 1 year. For example, a replacement rate of 1.0 percent signifies that the entire system is replaced once every 100 years.

The estimated replacement rates ranged from 0.46 percent (entire system replacement once every 217 years) to 0.63 percent (entire system replacement once every 159 years) to 1.54 percent (entire system replacement once every 65 years) to 2.0 percent (entire system replacement once every 50 years). For their 20-year statistical analysis, AWWA used a replacement rate with a uniform distribution, assuming a minimum of 0.5 percent and a maximum of 1.5 percent. Approximately 26 percent to 45 percent of the transmission pipe has a diameter smaller than 20.3 cm (8 in), 54 percent to 72 percent is between 20.3 and 50.8 cm (8 and 20 in), and 0.4 percent to 2.2 percent is 50.8 cm (20 in) or greater. The range of estimated replacement costs for pipe varied from $289/m for 20.3-cm-diameter pipe ($88/ft for 8-in-diameter pipe) to $866/m for a 61-cm-diameter pipe ($264/ft for 24-in-diameter pipe). It was recognized that these values depend on many factors, including the location of the pipes, the current age of the system, and the local importance of the system. The calculations for the total expected amounts were made using a sensitivity analysis with the above-mentioned values. The AWWA study did not include estimates for treatment, storage, and source infrastructure needs. For the total infrastructure needs, AWWA calculated the infrastructure distribution needs for medium and large systems, and used the EPA estimate for small systems.[3]

To compare the EPA report with the AWWA report, both must be expressed in 1998 dollars. The $325 billion AWWA estimate is approximately 3.9 times that generated by the EPA for its 20-year assessment of transmission needs, amounting to $84 billion (1998 dollars) [$77.2 billion in 1995 dollars]. The reasons identified for the larger AWWA estimate were the undefined time period for the costs due to utilities probably reporting only 5- to 6-year needs, the underestimated or overlooked future costs due to the short period of capital investment plans, the unreported distribution needs of one-half to three-quarters of the surveyed large utilities, and the possible underestimation of large utilities. In addition, the EPA did not collect data on the miles of pipes in place, the types of pipes used, and the water system data, such as population served or total service area.

## WIN – Clean and Safe Water for the 21st Century – 2000

In April 2000, the Water Infrastructure Network (WIN), a coalition of more than 20 drinking water suppliers, wastewater treatment companies, municipal and state government agencies, engineering organizations, and environmental groups, including AWWA, published a report called *Clean and Safe Water for the 21st Century*.(9) The objective of this report was to compare the current investments in water infrastructure with the investments that will be needed annually over the next 20 years to replace aging and failing pipes and to meet the mandates of the Clean Water Act and the Safe Drinking Water Act.

WIN handled the infrastructure replacement costs somewhat differently in the case of water supply compared to wastewater treatment. For water supply estimates, WIN adopted the method used by AWWA in their 1998 report.(8) This method used a simulation model to project the future costs of replacing distribution systems at then-current

---

[3] EPA defines "large systems" as serving more than 50,000 people, "medium systems" as serving 3,301 to 50,000 people, and "small systems" as serving 3,300 people or fewer.

costs. Unfortunately, WIN failed to report how they re-evaluated the replacement rates estimated by AWWA. If the same replacement rates were used, then they would be in the range of 0.46 to 2.0 percent. For wastewater, WIN used a model based on a method first developed by the U.S. Department of Commerce.(10) The model assumed that 1/20 of the depreciated value of all wastewater systems nationwide would be replaced each year over the next 20 years. This means that WIN assumed a replacement rate of 5.0 percent for the wastewater sector. The reason for the large difference between the replacement rates for the two sectors was not given.

WIN estimated that there will be a total annual capital investment and financing need of $46 billion during the next 20 years. Therefore, the total estimated 20-year need is $920 billion. The $46 billion annual need value includes $24 billion for drinking water and $22 billion for wastewater infrastructure and capital investment financing. If operations and maintenance are added, the total annual need is $96 billion, which is equivalent to an estimated $1.920 trillion in 20 years. WIN refers to its source as Hagler Bailly Services, Inc., which based its estimates on data and analyses conducted by AWWA, the U.S. EPA, the U.S. Bureau of the Census, and the U.S. Department of Commerce; however, the details on the calculations were not included in their report.

Different from the EPA report, which addressed the drinking water transmission piping infrastructure only, and the AWWA report, which addressed drinking water transmission systems only, the WIN report addressed both drinking water and sewage water infrastructure. WIN reported that the costs of replacing aging water facilities with new ones are much greater than previous estimates by EPA. Table 4 shows the estimates for operations and maintenance (O&M) costs, financing costs, and capital investment costs.

Table 4. Combined annual drinking water and wastewater infrastructure needs, according to the 2000 WIN report.(9)

| | **INVESTMENT NEEDS ($ x billion)** | **CURRENT INVESTMENTS ($ x billion)** | **SPENDING GAP (Year 2000 U.S. dollars) ($ x billion)** |
|---|---|---|---|
| Operations and Maintenance | 49 (51%) | 38 (58%) | 11 |
| Financing | 10 (10%) | 10 (15%) | 0 |
| Capital Investments | 37 (39%) | 18 (27%) | 19 |
| **TOTAL** | **$96** | **$66** | **$30** |

Table 4 shows that a total annual investment gap of $30 billion exists. Filling this gap will require a redistribution of allocations from 58 percent 15 percent 27 percent to 51 percent 10 percent 39 percent for the three cost categories, respectively. This redistribution indicates a significant increase in capital investments, both in absolute value ($18 billion to $37 billion) and in percentage of the total costs (27 percent to 39 percent). It is noted that the $30 billion gap calculated above is $4 billion lower than the $34 billion gap presented in the WIN report itself. The reason for this gap is that the WIN report is unclear about the individual costs for current operations and maintenance, financing, and capital investments.

The cost of taking action to guarantee a sufficient water quantity and a satisfactory water quality is traditionally recovered through customer rate increases. WIN reports that local homeowners and industries currently pay more than $60 billion a year in water and sewer charges. It is WIN's opinion that federal funds are needed amounting to nearly a trillion dollars in critical water and wastewater investments over the next two decades. These federal funds are meant to prevent significant rate increases for large portions of the U.S. population.

## Comparing the Three Reports

A comparison of the EPA report, the AWWA report, and the WIN report reveals that the estimated infrastructure costs were estimated by each organization using a different focus and different calculation methods. The estimated 20-year costs ranged from $138.4 billion (EPA, transmission pipe for drinking water only, no financing, no capital investments) to $325 billion (AWWA, drinking water transmission only, no financing, no capital investments) to $1.02 trllion for drinking water and $900 billion for sewage water (WIN, operations and maintenance costs, financing, and new capital investment costs included). Table 2 summarized and compared the three reports.

### Estimating the Total Cost of Corrosion

In all three reports, the costs for replacement and the costs for system expansion are treated equally. In the current research, no reference to studies was found that would estimate the division of these costs any differently than 50 percent/50 percent; therefore, in the next calculation, it is assumed that at least 50 percent of the transmission and distribution maintenance needs are used to replace aging (corrosion) infrastructure, while the other 50 percent would be for system expansion.

The EPA study estimated that transmission and distribution water piping represented 56 percent of the total cost. Using the AWWA study cost of $325 billion per 20 years for transmission water piping gives an estimate of the total drinking water infrastructure of $580 billion per 20 years (100 / 56 x $325 billion). This number is comparable to the $540 billion estimated by WIN (see table 2).

WIN estimated the current annual cost for new investments, operations and maintenance, and financing of the national drinking water system at $38.5 billion per year, and of the sewer system at $27.5 billion per year, as explained in table 2. The total cost of corrosion was estimated from these numbers by assuming that at least 50 percent of the operations and maintenance costs are to replace aging (corrosion) infrastructure, while the other 50 percent would be for system expansions. This results in an estimated cost of corrosion for drinking water systems of $19.25 billion per year and for sewer systems of $13.75 billion per year. In addition to the cost of replacing aging infrastructure, there is the cost of unaccounted-for water. Nationally, it is estimated that approximately 15 percent of the treated water is lost. Adding these three major cost items results in a total annual cost of corrosion of $36.0 billion per year for drinking water and sewer systems combined.

## AREAS OF MAJOR CORROSION IMPACT

Corrosion damage costs money, but so does corrosion control. Corrosion can occur at the treatment plant, throughout the distribution system, and in household plumbing. Wherever it occurs, it has effects that cost both the utilities and the consumers money. Corrosion results in pipe breaks and leaks; damage to water meters, plumbing components, and storage facilities; excessive repairs and replacement, increasing both operating and capital expenses; and water loss.

In the current sector study, the total annual corrosion cost for drinking and wastewater systems combined was estimated at $36 billion per year. In the past, estimates of the total annual cost of corrosion damage incurred by water utilities have ranged from $1.7 billion(11) up to 25 percent of total annual operating costs,(12) which has been estimated at $5 billion.(13) Estimates of the cost of corrosion damage to consumers ranges from roughly equal the cost to utilities(14) to double their cost.(15) The large variations in these estimates may have been because of limited data; however, in the current study, national estimates and extrapolations were used.

In 1989, Levin et al.(16) compared specific chemical treatments for internal corrosion control by modeling variables such as dosage rate and system size. Although this method can be used for individual systems, it cannot be easily extrapolated to estimate national corrosion costs. The above authors also included data from several studies that compared corrosion costs in the 1970s and early 1980s. In table 5, one column shows the percentage cost of corrosion damage that could potentially be avoided through improved water treatment, according to the various researchers cited.

Table 5. Estimates of annual per capita corrosion damage (1998 dollars*), as summarized in a 1989 overview article by Levin et al.(16)

| **STUDIES** | **ESTIMATED ANNUAL CORROSION DAMAGE (per capita)** | | | **CORROSION DAMAGE AVOIDABLE THROUGH WATER TREATMENT** | **ANNUAL PER CAPITA BENEFITS OF CORROSION CONTROL** | **ASSUMPTIONS/NOTES** |
|---|---|---|---|---|---|---|
| | **Distribution Systems** | **Residential** | **Total** | | | |
| Kennedy Engineers (1973) | $8.36 | - | $25.07** | 30% | $7.52** | Assumed 30% potential reduction in corrosion damage and that distribution costs were one-third of total costs. |
| Hudson & Gilcreas (1976) | $10.02** | - | $39.06** | 50% | $19.53** | They did not include increased operating costs. Per capita estimate assumes 200 million people are served by public water systems. Assumed that distribution costs were one-third of total costs. |
| Kennedy Engineers (1978) | - | $46.31** | $69.45** | 20% | $13.89** | They calculated $6.17 per capita in savings to residence owners. Assumed residential costs were two-thirds of total costs. |
| Bennett et al. (1979) cited in Ryder (1980) | $14.10 | - | $42.30** | 20% | $8.46** | Assumed that 200 million people are served by public water systems and that distribution costs were one-third of total costs. |
| Energy & Environmental Analysis | $5.97 | $11.96 | $17.93 | 38% | $6.81 | This is an admitted underestimate. It includes only damage to pipes (not damage to water heaters, increased operating costs, etc.). |
| Ryder (1980) | $1.76 | $33.29 | $35.04 | 25% | $8.76 | Ryder ascribed 95% of corrosion damage to private owners. |
| Kirmeyer & Logsdon (1983) | - | $35.40** | $53.10** | 40% | $21.24** | Assumed residential costs were two-thirds of total damage. |
| **AVERAGE** | **-** | **-** | **$40.28** | **32%** | **$12.31** | |

*In the current table, all amounts reported by Levin et al. in 1985 were multiplied by 1.5 to calculate 1998 dollars.
**These estimates have been calculated by Levin, Schock, and Clark.(16)

In the following sections, the areas of major corrosion impact in the drinking water and sewer services sector are identified. These areas include water quality, water quantity, unaccounted-for water, water main line breaks, internal corrosion in water systems, and external corrosion in water systems.

## Water Quality

The two greatest concerns of water utilities are the quality and the quantity of water supplied to customers. Water quality is determined by serviceability (color, taste, and odor) and the health requirements. Corrosion may affect both of these factors. All aspects of water quality can be affected by corrosion of water handling equipment and piping. For example, corrosion products from welded steel piping and iron piping may cause complaints about red or yellow "rusty" water, and internal corrosion of copper and lead piping and corrosion of joint soldering can pose health risks due to increased human exposure to these elements. Microbiologically influenced corrosion (MIC) may affect water quality, both in the health aspects and in the color, taste, and odor of the delivered water.

## Water Quantity

The quantity of water is measured directly after it leaves the water treatment facilities and just before it reaches the consumer. In terms of corrosion, the relevant water quantity is that of the unaccounted-for water. The quantity of water reaching the customers can be significantly decreased by leaks in the system. Although the cause of a leak may be internal or external corrosion, or in general terms, “system aging,” it is usually not strictly reported as such. Utilities report leaks in the water system as one of the major factors in unaccounted-for water.

## Unaccounted-For Water

In the current research, corrosion experts and maintenance engineers at various water utilities were interviewed to give their estimates of unaccounted-for water. The estimates ranged from 5 percent to 40 percent, depending on whether unaccounted-for water included unauthorized use of water only, or if it included all water lost between the producer and the consumer. The water utility annual reports from Denver, CO,(17) Columbus, OH,(18) and El Paso, TX(19) were reviewed to obtain an estimate of unaccounted-for water. These reports indicated unaccounted-for water as approximately 5.34 percent (1999, treated versus sales), 19.39 percent (1972-1997, pumped versus metered), and 12.70 percent (10-year average, 1988-1997, pumped versus billed), respectively (see table 6). Considering the spread in these values, a national average of 15 percent unaccounted-for water was assumed for calculations in the current report.

A least-conservative estimate of the percentage of unaccounted-for water can be calculated from the difference between the amount of treated water and the amount of metered (paid for) water. Within the total quantity of unaccounted-for water, the percentage attributed to system aging or leaks is generally not known; however, based on the review of several utility annual reports, a reasonable estimate appears to be about 50 percent.

Unaccounted-for water consists of two categories: authorized and lost. Examples of authorized, unmetered water uses include firefighting, fire hydrant flushing, main line flushing, process water for water plants, irrigation of public areas such as parks and highway medians, and street cleaning. Unauthorized, unmetered uses include water theft through illegal connections. Other causes of unaccounted-for water include unmapped or forgotten piping, evaporation, reservoir seepage, reservoir overflow, and oversized or inaccurate water meters; therefore, small leaks or minimal water usage may not be registered. Meters are originally installed according to anticipated user patterns; however, if the consumer's patterns change, a utility rarely resizes a meter to match this. Most water utilities are well aware of the difference in produced and metered water, and have teams to find and repair leaks and faulty meters. However, the magnitude of their systems and their overall deteriorating integrity as the water systems age make it a difficult task.

Table 6. Summary of estimated fraction of unaccounted-for-water for selected U.S. cities, as reported in various sources.(17-19)

| CITY | YEAR | DEFINITION | BILLED | UNACCOUNTED FOR | $m^3$ LOST | RETAIL PRICE | LOST REVENUE |
|---|---|---|---|---|---|---|---|
| | | | % | % | x million | \$ / $m^3$ | \$ x million |
| Denve, COr | 1999 | Treated versus Sales | 94.66 | 5.34 | 15.195 | 0.4438*** | 6.7 |
| Denver, CO | 1998 | Treated versus Sales | 92.66 | 7.34 | 21.531 | 0.4438*** | 9.6 |
| Columbus, OH | 1972-1997 | Pumped versus Metered | 80.61 | 19.39 | 28.341 | 0.8137** | 23.0 |
| El Paso, TX | 1988-1997 | Pumped versus Billed | 87.30 | 12.70* | 19.097 | 0.3461** | 6.6 |
| San Francisco, CA | - | Pumped versus Metered | - | 5 to 10***** | - | - | - |
| **UNITED STATES** | **Annual** | **Total Lost Water** | **85%** | **15% of<br>56.7 billion $m^3$** | **8,505** | **\$0.3513****** | **\$2,988** |

*10-year average.
**1997 value.
***1999 value.
****Average value, as reported by Institute for Research in Construction (IRC).
*****Estimated by Steven Leonard, San Francisco Water Department.

Unaccounted-for water is a serious problem nationwide. The water that disappears represents lost revenues and increased costs for water utilities. On the other hand, unaccounted-for water losses may create the impression that additional water supplies and/or distribution systems are needed, when all that is really required is reducing waste in the system. Unaccounted-for water losses may also increase the infiltration of outside water into wastewater treatment plants, resulting in greater volumes to process and increased costs to be paid.

An approximate revenue loss calculation for unaccounted-for water is done by multiplying the estimated annual total quantity of 56.7 billion $m^3$ (15 trillion gal) of treated water by an estimated 15 percent unaccounted-for water and the cost of that water. A lower bound calculation is done by assuming an average treatment cost of about \$5.29/thousand $m^3$. In that case, the lost revenue cost for unaccounted-for water is: 56.7 billion $m^3$ x 15 percent x \$0.00529/$m^3$ = \$45 million. An upper bound calculation is done by assuming an average consumer cost of about \$0.3513/ $m^3$. In that case, the lost revenue cost for unaccounted-for water is: 56.7 billion $m^3$ x 15 percent x \$0.3513/$m^3$ = \$2.988 billion. These calculations show that the annual direct cost of unaccounted-for water ranges between \$45 million and \$3.0 billion.

## Water Main Line Breaks

Transmission and distribution line breaks are another large factor affecting water quantity. The direct cost of a break depends on the material, labor and equipment costs of the excavation, the actual repair and/or replacement, and repaving. These costs are influenced by the emergency level of the break and the location of the break in the city. Indirect costs are calculated as the costs of the consequences to others and they are much more difficult to estimate. For example, a street under construction will cause time delays for the traffic passing there and businesses may be affected by the water shortage and claim the liability of the utility. Customers experience inconvenience from the outage because the system is temporarily out of service and the water will remain dirty for a period of time following the pipe break. Dealing with the customer complaints places a heavy burden on the service departments of utilities.

## Internal Corrosion in Water Systems

Forms of internal corrosion in water systems include uniform corrosion, galvanic corrosion, localized corrosion, concentration cell corrosion, microbiologically influenced corrosion (MIC), and erosion-corrosion. Major internal corrosion can occur in pipes made of cast iron, ductile iron, steel, galvanized steel, and cement-based materials. Table 7 summarizes corrosion types for different piping materials and the possible tap water quality problems caused by them, as described by the AWWA Research Foundation in 1996 in a reference book on internal corrosion of water distribution systems.(20)

Negative health effects can result from corrosion of lead, corrosion of copper alloys and solder in water supply systems, and corrosion of copper plumbing in potable water systems. In the current report, an effort is made to provide background on the most significant corrosion mechanisms, as related to their cost impact.

Table 7. Corrosion and water quality problems caused by materials in contact with drinking water.(20)

| MATERIAL | CORROSION TYPE | TAP WATER QUALITY DETERIORATION |
|---|---|---|
| Cast Iron | Uniform Corrosion | Rust Tubercles (Blockage of Pipe) |
| Ductile Iron | Graphitization and Pitting Under Unprotective Scale | Iron and Suspended Particles Release |
| Steel | Pitting | Rust Tubercles (Blockage of Pipe) and Iron and Suspended Particles Release |
| Galvanized Steel | General Corrosion | Excessive Zinc, Lead, Cadmium, and Iron Release and Blockage of Pipe |
| Asbestos Cement* | Uniform Corrosion | Calcium Dissolution, Possible Asbestos Fibers, and Increased pH |
| Concrete | Uniform Corrosion | Calcium Dissolution and Increased pH |
| Cement Mortar** | Uniform Corrosion | Calcium Dissolution and Increased pH |
| Copper | Uniform Corrosion | Copper Release |
| | Localized Attack | Perforation of Pipe and Leakage |
| | Microbiologically Influenced Corrosion (MIC) | Leakage From Pipes |
| | Corrosion Fatigue | Rupture of Pipe and Leakage |
| | Erosion-Corrosion | Leakage From Pipes |
| Lead Pipe | Uniform Corrosion | Lead Release |
| Lead-Tin Solder | Uniform Corrosion | Lead and Tin Release |
| Brass | Erosion and Impingement | Penetration Failures |
| | Dezincification | Blockage of Pipe |
| | Stress Corrosion Cracking (SCC) | Lead and Zinc Release |
| Plastic | Degradation by sunlight and microorganisms? | Taste and Odor |

*No internal lining (e.g., tar).

**Used as internal lining of iron and steel materials.

## External Corrosion in Water Systems

External corrosion of water systems may be caused by general corrosion, stray current corrosion, microbiologically influenced corrosion (MIC), and/or galvanic corrosion. Mitigation techniques include the application of protective coatings, wrapping pipe in a plastic, and the application of cathodic protection. The areas of major external corrosion impact are generally those where localized attack may take place, such as in the proximity of other systems (galvanic corrosion) or in areas where stray currents may occur.

Both dc and ac stray currents on a water line can cause corrosion. Stray current studies, for example, those performed by the AWWA Research Foundation,(21) show that the corrosion rate due to dc current is generally greater than the corrosion rate due to ac current. General external corrosion can be a problem in corrosive soil, particularly when there is low soil resistivity, high moisture content, and corrosive chemical species present. When piping is electrically continuous (welded steel piping), cathodic protection can be applied; however, that is generally not possible for discontinuous pipe (ductile iron, cast iron).

Plastic piping [for example, polyvinyl chloride (PVC) piping] does not show metallic corrosion, but its properties do deteriorate over time. In severely corrosive soils, PVC piping may be selected rather than a metallic piping material because it is inert to the chemical conditions. PVC has a lower density than steel and iron; therefore, it is relatively easy to handle in the field. However, PVC also has lower strength, and traditional welding is not possible. PVC has been used for a relatively short time, compared with steel and iron water lines. Therefore, there is limited data on the expected service life of PVC pipelines, and calculations of comparative total life-cycle costs were not found.

Cement-based piping deteriorates by corrosion of the reinforcement steel, which is often accelerated by chloride from salt-treated roads during winter. Corrosion occurs when the passive surface film that naturally forms on steel in high-pH concrete/cement breaks down in the presence of chloride. The corrosion product has greater volume than the original steel, creating internal stresses that cause cracking and spalling of the concrete/cement pipes.

## CORROSION CONTROL METHODS

Table 8 summarizes the most commonly used corrosion control methods for water systems. For each component, several different control methods can be applied.

Table 8. Summary of most commonly used corrosion control methods for water systems.

| COMPONENTS IN WATER SYSTEM | CORROSION CONTROL METHOD |
|---|---|
| Steel dams | Increased wall thickness |
| General water infrastructure | Corrosion inhibitors |
| | pH adjusters |
| | Alkalinity controllers |
| | Hardness controllers |
| Storage tanks | Cathodic protection (CP) |
| | Internal coatings |
| | External paint coatings |
| Ductile iron, cast iron, and steel pipes – Internal corrosion | Internal linings |
| | Internal inspection |
| Cement-based pipe | Internal lining – cement mortar |
| Ductile iron, cast iron, and steel pipes – External corrosion | Cathodic protection (CP) |
| | External coatings |
| | Corrosion coupons, test stations, corrosion data loggers |
| Lead pipe | Replacement with copper pipe |
| Copper pipe | Prevention, by improved tube production |
| Nonferrous alloys –<br>Fittings, fixtures, joints | Replacement with corrosion-resistant components |
| Sewage pipes | Increased wall thickness |

## Corrosion Control in the Water Supply

Each water utility tries to have a sufficiently large supply of water to fulfill the needs of its customers. Rainwater is the main source for groundwater, while river water and lakes are the main source for surface water. Lakes and underground reservoirs are used to store large quantities of raw water for times when the water level in a river is too low. Infrastructure in and connected to the reservoirs includes dams, water-intake structures, and piping. Corrosion is generally not a very significant issue here. For example, metal dams are given a corrosion tolerance with regard to the thickness of the steel walls, allowing for metal loss due to general corrosion during the expected service life.

## Corrosion Control in Water Treatment Facilities

The infrastructure of water treatment facilities is designed to remove contaminants from water. Figure 1 shows a schematic diagram of the drinking water treatment process.

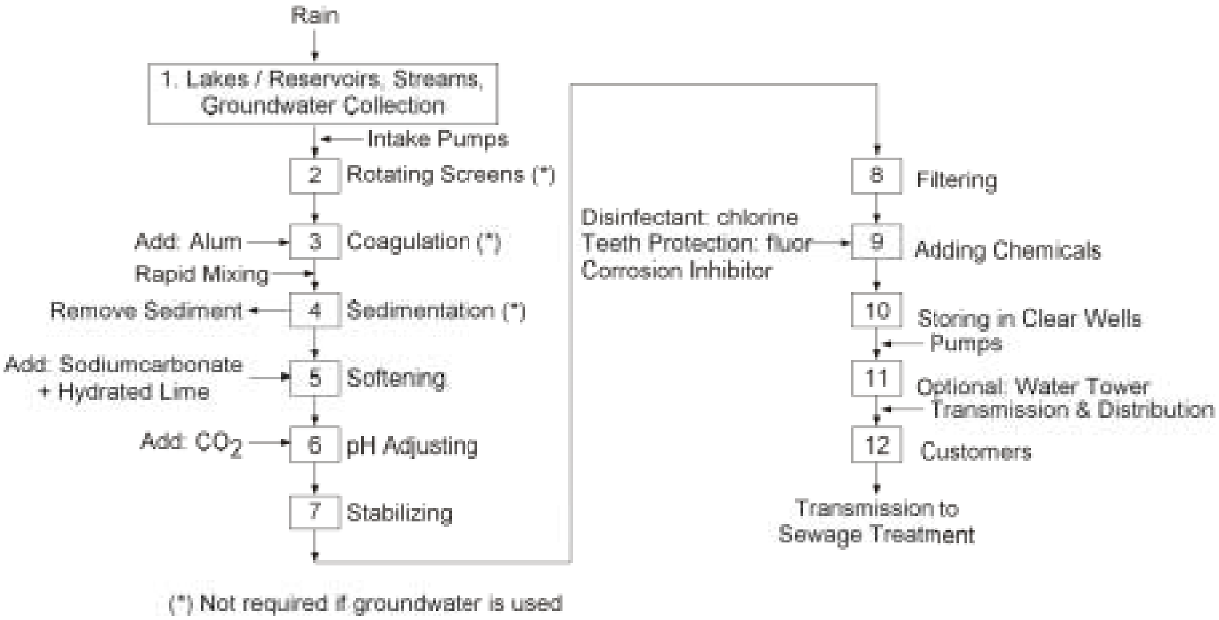

Figure 1. Schematic diagram of drinking water treatment process.

A series of filtration procedures and several chemical treatments are used in cleaning the raw water to prepare it for consumption. Mixing of different source waters is often used as an option to change quality and reduce corrosivity. In some cases, aeration can be used in drinking water treatment. In addition to removing hydrogen sulfide, methane, radon, iron, manganese, and volatile organic contaminants, aeration is effective for carbon dioxide ($CO_2$) removal. $CO_2$, in turn, directly affects pH and dissolved inorganic carbon, two parameters that significantly influence lead and copper solubility. Under the right water quality conditions, aeration can serve as a potential corrosion control treatment by removing $CO_2$ and subsequently increasing pH and decreasing dissolved inorganic carbon. The degree to which aeration affects corrosion depends on such raw water quality parameters as pH, dissolved inorganic carbon, and dissolved oxygen, as well as $CO_2$ removal efficiency.(22)

The chemicals used to treat the raw water and improve its quality include corrosion inhibitors, pH adjusters, and alkalinity and hardness controllers. The commonly used water treatment chemicals are soda ash, sodium bicarbonate, sodium hydroxide (caustic soda) plus carbon dioxide, lime, alkaline media filters, and combinations such as limestone slurry plus carbon dioxide plus sodium hydroxide. All U.S. water utilities are required to continuously monitor their water quality by taking and analyzing samples of their treated water. The samples are taken at regular time intervals and at different locations spread out over the system.

## Corrosion Inhibitors, pH Control, and Alkalinity Adjusters

In addition to the necessity of water quality control according to the Safe Drinking Water Act (SDWA), the application of chemicals for pH adjustment is one of the main options of internal corrosion control. In many instances, however, pH control or pH and alkalinity adjustment are not sufficient to suppress corrosion problems. In these cases, corrosion inhibitors can be used for internal corrosion protection. Corrosion inhibitors are chemicals that are dosed in small quantities for a significant reduction in corrosion. The impact of inhibitors on water quality and their effectiveness on different materials are very complex.(23) The stringent limits concerning lead and copper, or other materials in drinking water, limit the use of inhibitors for corrosion control.

Categories of corrosion inhibitors for water treatment include naturally occurring inhibitors and human-added inhibitors. Natural inhibitors include natural organic matter, dissolved silica, and phosphate. Materials that can receive some degree of corrosion protection from natural inhibitors include iron, zinc coatings, lead, and copper. Added corrosion inhibitors are chemicals that are dosed in small quantities to obtain a passivating film on anodic sites to suppress the electrochemical corrosion reactions or to act to inhibit the cathodic reactions and, therefore, provide a significant reduction in corrosion rate. Added corrosion inhibitors include orthophosphates, molecularly dehydrated polyphosphates, bimetallic (zinc-containing) phosphates, silicates, and phosphate-silica mixtures.

## Selection of Corrosion Inhibitors

The selection of the most cost-effective corrosion inhibitors is a complex task that depends on many interacting variables. The cost-effectiveness can be calculated by multiplying the relative effectiveness of the inhibitor, the necessary dosage rate (mg/L), and the price per weight ($/kg).

$$\text{Cost Effectiveness} = \text{Relative Effectiveness} \times \text{Dosage Rate} \times \text{Price Per Weight}$$

The inhibitor dosage rate depends on the local water condition and temporal factors, such as time of the year. It should be quantified in terms of percent reduction of corrosion and extension of useful life. Table 9 lists commonly used corrosion inhibitors for potable water systems, their dosage rates, and a comparative estimated inhibitor cost.(20) In 1995, the American Water Works Company (AWWC), a privately owned company serving about 5.1 million people, reported the costs of chemicals for their system.(24) These costs are included in table 9 and comparison shows that the estimates are in reasonable agreement with the AWWA estimates. AWWA estimated that if a treatment cost of $5.29 per thousand m$^3$ ($20 per million gal) is assumed, the annual costs for corrosion inhibitor treatment would range between $1.00 and $1.50 per residential consumer.

In a 1985 publication by Singley et al.,(25) typical annual chemical costs for corrosion control were presented, based on 1982 data from various chemical suppliers. These figures were used to estimate the cost range per year for an 11.4 thousand m$^3$-per-day [3 million gal-per-day (MGD)] plant and a 189 thousand m$^3$-per-day (50-MGD) plant. The results are given in table 10.

Phosphate and silicate corrosion inhibitors have been used, with or without pH control, to reduce metal release and to prolong the service life of distribution systems or domestic installations. If concentrations are limited, inhibitors may not avert localized corrosion (such as pitting) caused by material or installation faults, or they may not be able to reduce corrosion rates of the usual materials (galvanized steel, steel, cast iron, copper, or lead) sufficiently to extend the life span of a system beyond 75 to 100 years. Corrosion inhibitors are often necessary and can be very beneficial when concerns about water quality deterioration have to be resolved. However, there are secondary influences of corrosion inhibitors such as the impact of zinc orthophosphate on zinc levels in wastewater sludges, or phosphate levels in open reservoirs. Unfortunately, there is no simple solution for balancing water quality, health risks, system reliability, and environmental impact. Cooperation between plant owners and the concerned government agencies benefits system optimization for corrosion management.

Table 9. Commonly used corrosion inhibitors for potable water systems, dosage rates in milligrams per liter (mg/L), and comparative estimated inhibitor costs in 1994 dollars.[20,24]

| **INHIBITOR TYPE** | **DOSAGE RATE** | **INHIBITOR COST** | **TREATMENT COST ESTIMATED BY AWWA** | **TREATMENT COST ESTIMATED BY AWWC** |
|---|---|---|---|---|
| | **mg / L** | **$ / kg*** | **$ per million liters**** | **$ per million liters**** |
| Lime | 10 – 30 | 0.04 | 0.53 – 1.59 | - |
| Caustic Soda | 10 – 30 | 0.44 | 2.65 – 3.97 | 3.44 – 11.90 |
| Soda Ash | 10 – 30 | 0.27 | 4.42 – 13.23 | 3.97 – 4.76 |
| Sodium Hexa-Metaphosphate | 1 – 4 ($PO_4$) | 2.00 ($PO_4$) | 1.98 – 7.94 | - |
| Bimetallic Phosphate | 0.5 – 2 ($PO_4$) | 3.33 ($PO_4$) | 1.65 – 6.61 | - |
| Zinc Orthophosphate | 0.1 – 0.5 (Zn) | 4.99 ($PO_4$) | 0.53 – 6.61 | 2.12 – 4.50 |
| Sodium Silicate | 4 – 10 ($SiO_2$) | 0.67 ($SiO_2$) | 2.65 – 6.61 | - |
| Carbon Dioxide | 5 – 10 | 0.11 | 0.53 – 1.06 | - |
| Phosphoric Acid | 0.5 – 3 (P) | 1.33 ($PO_4$) | 0.79 – 4.76 | - |
| Monosodium Phosphate | 0.5 – 3 (P) | 2.66 ($PO_4$) | 1.59 – 9.52 | - |
| Ortho-Polyphosphate Blend | 0.2 – 1 ($PO_4$) | 5.54 ($PO_4$) | 1.06 – 5.29 | - |

*To obtain $/lb, multiply $/kg by 0.455.

**To obtain $/million gal, multiply $/million liters by 3.787.

Table 10. Typical annual chemical costs (1998 dollars) for common chemicals used for corrosion control based on data* from various chemical suppliers and reported by Singley et al.[25]

| **CHEMICAL** | **USE** | **FEED RATE** | **COST PER UNIT ($)** | **COST PER YEAR** | |
|---|---|---|---|---|---|
| | | | | **11.4 THOUSAND $m^3$-PER-DAY (3-MGD PLANT) ($)** | **189 THOUSAND $m^3$-PER-DAY (50-MGD PLANT) ($)** |
| Quicklime, CaO | pH adjustment | 1 – 20 mg/L<br>8 – 170 lb/MG | 95/ton bulk | 416 – 8,798 | 6,750 – 146,550 |
| Hydrated lime, $Ca(OH)_2$ | pH adjustment | 1 – 20 mg/L<br>8 – 170 lb/MG | 117/ton bag<br>98/ton bulk | 513 – 10,868<br>428 – 9,068 | 8,550 – 181,500<br>7,125 – 151,500 |
| Caustic soda, NaOH (50% solution) | pH adjustment | 1 – 20 mg/L<br>12 – 150 lb/MG | 300/ton bulk | 1,965 – 32,850 | 41,100 – 684,000 |
| Soda ash, $Na_2CO_3$ | pH adjustment | 1 – 40 mg/L<br>8 – 350 lb/MG | 24/cwt bag<br>228/ton bulk | 2,103 – 91,980<br>999 – 45,563 | 35,100 – >1,500,000<br>16,650 – 759,000 |
| Inorganic phosphates | Inhibitor | 3 mg/L<br>25 lb/MG | 98/cwt bag | 26,700 | 445,500 |
| Sodium silicate | Inhibitor | 2 – 8 mg/L<br>17 – 67 lb/MG | 8/cwt tank | 1,395 – 5,505 | 23,250 – 91,800 |

*The values are given in 1998 dollars by multiplying the original data by 1.5. The costs do not include freight.

## Corrosion Control in Water Storage Systems

After treating the raw water in treatment facilities, the clean drinking water can temporarily be stored in utility water towers in aboveground or underground tanks, or underground clear wells. The areas of major corrosion impact are internal corrosion of the storage towers and tanks, and external corrosion due to weather conditions. If left unattended, both internal and external corrosion may pose a structural risk due to loss of wall thickness. Therefore, regularly scheduled corrosion inspections of water tanks and water towers should be conducted. With regular maintenance, water tanks can have a useful life of more than 100 years.

The dominant forms of internal corrosion include general corrosion, galvanic corrosion, and microbiologically induced corrosion in standing water. The microbiological contaminants are regulated under the Surface Water Treatment Rule (SWTR) and the Total Coliform Rule (TCR). Corrosion control methods for these types of corrosion are cathodic protection and lining or painting of the interior of the tanks. Cathodic protection is usually performed on a project basis, while painting generally is performed as part of long-term maintenance programs.

External corrosion originates from moisture, rain, and changing weather. Generally, tanks and water towers are designed with a so-called corrosion allowance. This is an allowable rate of general corrosion. The corrosion rate can be determined by measuring the remaining wall thickness of a storage tank at given time intervals. If the corrosion rates are within the design limits and the remaining wall thickness is thick enough, then the tank is generally expected to be structurally fit for service. The common corrosion control method is painting the tower or tank. Deterioration of the appearance of water towers by external corrosion is another consideration for painting.

The costs for corrosion control for water storage tanks are determined by the type of cathodic protection and the type of protective coatings utilized. In 1991, Robinson(26) presented comparative case studies of the economics of corrosion protection systems. Robinson argued that many thousands of dollars are spent unnecessarily to re-coat and repair interior coatings when cathodic protection would mitigate further corrosion activity and prolong the necessity of coating maintenance. Using economic models, this author determined that long-term cost benefits can be realized with the application of cathodic protection to water storage tanks.

## Corrosion Control in Water Transmission Systems

The water is pumped from the temporary storage or is pumped directly from the treatment facilities through large-diameter transmission water pipes. The transmission water piping system is regulated with large valves, where water quantities are measured using large-capacity water meters. The most common materials of construction for transmission pipe include cast iron, ductile iron, prestressed concrete, asbestos concrete, PVC, and welded steel piping. Except for PVC, all of the above materials contain ferrous metal components that must be protected.

Table 1 shows that approximately 67 percent of the U.S. transmission water lines are built from cast iron and ductile iron. Ductile iron pipe is manufactured in 5.5- or 6.1-m (18- or 20-ft) nominal laying lengths and 7.6- to 163-cm (3- to 64-in) diameters in a range of standard pressure classes and nominal wall thicknesses. Since its introduction in the marketplace in 1955, ductile iron pipe has been used extensively for drinking water and wastewater systems. Pipes are made from the manufactured sections of pipe, with a bell-and-spigot connection sealed with rubber O-rings.

The most common failure mechanisms of such pipes are uniform corrosion (external or internal), graphitization, and pitting under unprotected corrosion scales. Loose rust tubercles may cause blockage of a water pipe where these particles reach consumers. The only corrosion control methods for loose particles is prevention through the addition of corrosion inhibitors to protect the inside pipe walls or internal lining of the pipes. For ductile iron and cast iron pipes, a standard portland cement mortar lining is the most common internal lining. Other lining types include specialty cement mortars, epoxies, polyethylene, and polyurethane. In some instances, coal tar has been used for internal linings; however, concerns about possible health effects and oily organic residue given off by coal tar coatings limit their use.

Table 1 further shows that a steel pipe is only used for approximately 4 percent of the U.S. transmission water lines. The use of steel water pipe dates back to the California Gold Rush of 1849,(27) when it was produced from thin riveted wrought pipe that could be slipped together. In 1905, a pressure-locking seam pipe was developed. In the early 1930s, methods of automatically welded steel pipe from rolled stock were developed. Since World War II, U.S. manufacturers have primarily produced spiral-welding steel pipe. The most common corrosion control methods for external corrosion of steel pipes are coatings or coatings and cathodic protection.

Developments in electronic equipment make internal inspection with cameras an option to evaluate the condition of pipe sections. However, these techniques are still quite expensive, the equipment insertion into and extraction from the pipe is usually difficult, and the pipe may have internal obstructions or bends. In addition, analysis of the data is generally time-consuming and difficult.

## Effect of Reduced Pipe Wall Thickness

Significant problems occur in older transmission pipes made from cast iron and ductile iron, as the wall thickness is reduced by corrosion until a leak occurs. Problems in newer iron pipes are similar to those found in older iron pipes, but occur after shorter periods of time because of decreased wall thickness. During the last 100 years, utilities have applied pipes of thinner wall because of the improved mechanical properties of steel; however, corrosion rates are generally independent of the strength of a material. For a given corrosion rate, a thinner wall will corrode through in less time than a thicker wall. Therefore, an effective corrosion control method is the selection of thicker wall pipe to provide a larger corrosion tolerance to wall thinning. Although thicker wall pipe is more expensive, this approach may be very cost-effective because of its long life and relatively low need for maintenance.

## Degradation of Cement-Based Materials

Approximately 17 percent of the U.S. transmission water lines are built from concrete and asbestos concrete materials (see table 1). Pipes made from these materials are usually assembled on location from factory-made pipe sections. Internal steel reinforcement wires and bars (rebar), steel mesh, and steel plates are used to provide tensile strength. Cement-based pipes are susceptible to corrosion when aggressive ions, such as chloride, migrate to the steel surface. The corrosion products take up more volume than the original steel, causing cracking of the concrete, further accelerating corrosion.

In asbestos cement pipes, asbestos fibers are used as reinforcement for tensile strength. With these pipes, the main concern is the release of asbestos fibers into the drinking water. Other effects of cement-based material deterioration include calcium dissolution (increased water hardness), increased pH values, increased alkalinity, and migration of aluminum into the drinking water. A common corrosion control method for concrete pipe is the application of internal protection using a cement mortar lining, which can be applied as a factory lining or as an *in situ* lining. One method of determining the quality of a lining is to measure its calcium oxide (CaO) leaching resistance, a function of the mortar density.

## Cement Mortar Linings

New iron and steel pipelines are commonly lined with cement mortar. Cement mortar linings are also used for rehabilitation of older ductile iron, cast iron, and steel water pipeline networks. The linings can eliminate limited leaks of pipes and pipe connections as a result of the high resistance of cement mortar to pressure, enhance the hydraulic characteristics of the mains, and prevent further internal corrosion damage. Table 11 shows the estimated costs for water pipe rehabilitation by cement mortar lining as a percentage of pipe replacement costs, as estimated by the AWWA.(20) The rehabilitation cost is broken down into four components: (1) cleaning and cement mortar lining; (2) excavation, pipe fitting, and restoration of the road surface; (3) materials; and (4) labor costs. The right column shows the percentage cost for rehabilitation compared with total pipe replacement.

Table 11. Estimated costs for water pipe rehabilitation by cement mortar lining, as a percentage of pipe replacement costs.(20)

| **INTERNAL DIAMETER** | | **CLEANING AND CEMENT MORTAR LINING** | **EXCAVATION, PIPE FITTING, RESTORATION OF ROAD SURFACE** | **MATERIAL** | **LABOR COSTS AND RELATED COSTS** | **COSTS FOR REHABILITATION IN RELATION TO PIPE REPLACEMENT** |
|---|---|---|---|---|---|---|
| **cm** | **inch*** | **%** | **%** | **%** | **%** | **%** |
| 8-15 | 3-6 | 33 | 49 | 7 | 11 | 39.5 |
| 20-30 | 8-12 | 33 | 48 | 7.5 | 11.5 | 41 |
| 50 | 20 | 22 | 55 | 13 | 10 | 33.2 |
| 60-80 | 24-32 | 37 | 47 | 8 | 8 | 19.4 |
| 100-120 | 40-48 | 30 | 57 | 5 | 5 | 13 |

*Equivalent inch measurements are calculated in rounded inches.

## External Corrosion of Transmission Piping

External corrosion mechanisms on transmission water piping include general or localized corrosion due to corrosive soils, galvanic corrosion through connections to other utilities and structures, MIC, ac stray current corrosion from power lines, and dc stray current corrosion from cathodic protection (CP) systems on nearby structures. Corrosion control methods to mitigate these forms of corrosion include the application of coatings and CP by installation of impressed current or sacrificial anode systems. External coatings on older water pipes include asphalt coatings and coal tar enamel coatings, while external coatings on new pipes include coal tar enamel coatings, polyethylene-based coatings, and fusion-bonded epoxy coatings.

## Cathodic Protection and Coatings

The CP design should be executed by specialists. After the CP installation, regular inspection of the system is required. For CP to be applied effectively, the pipe must be electrically continuous, which is usually only partly true for the bell-and-spigot type of pipe. Welded steel pipes are generally electrically continuous; therefore, CP may be easier to apply to those pipes. CP protection of pipelines is typically more effective when used as a supplemental system to a coating system. Without a coating system, the amount of electrical current (from either a sacrificial or impressed-current CP system) is typically too large to make CP economically feasible for water systems. For prestressed concrete pipe, CP can be used to supplement the protection provided by the standard mortar coating in aggressive soil environments.(28) However, care must be taken not to overprotect the prestressing steel.

There exist two types of CP systems: impressed-current systems that require rectifiers and periodic direct assessment consisting of inspection, monitoring, and adjustment by trained operators, and sacrificial systems that require less attention. Because of the ease of operation, a sacrificial anode system (consisting of buried zinc or magnesium anodes) is generally preferred for welded steel pipe. Federal regulations specify the frequency and the specifics of monitoring of CP systems on interstate natural gas and oil product pipelines. For water lines, however, no such regulations exist; therefore, it is uncertain if cities and municipalities conduct the necessary CP monitoring.

# Corrosion Control in Water Distribution Systems

Smaller diameter distribution pipes branch from the larger transmission pipes to supply the water to individual houses and businesses. The most common materials for distribution piping include ductile iron, PVC, copper, and piping. In these smaller diameter pipes, the corrosion problems and the corrosion control methods for ductile iron corrosion and the deterioration of PVC are similar to those described for the larger diameter pipes. A 1980 study performed for the Seattle (WA) Water Department(29) found that the cost of internal corrosion of consumer plumbing systems can be significantly higher than the cost of corrosion in large-diameter transmission systems. The study found that plumbing costs were 10 times higher for initial capital and 20 times higher for annual maintenance than transmission system costs.

A series of reports have suggested that increased use of chloramines for disinfection, as a means to reduce trihalomethane, accelerates corrosion and degradation of metals and elastomers common to distribution plumbing. In 1993, the AWWA Research Foundation(30) reported the results of a study comparing the oxidation effects of free and combined chlorine species on seven metal surfaces (mild steel, copper, brass, bronze, Pb/Sn solder, Sn-Sb solder, and Sn-Ag solder), seven basic elastomer types (natural rubber, acrylonitrilebutadiene, styrene-butadiene, chloroprene, silicone, ethylene-propylene, and fluorocarbon), and three thermoplastics. The results showed that, with few exceptions, solutions of chloramines produced greater material swelling, deeper and more dense surface cracking, a more rapid loss of elasticity, and greater loss of tensile strength than equivalent concentrations of free chlorine. Only the newly engineered, completely synthetic polymers developed specifically for their chemical resistance performed well in the chloramine exposures. The results further showed that, with regard to copper and its alloys, all tested chlorine disinfectants accelerated corrosion. In contrast to the elastomer experience, free chlorine exerted a higher oxidant effect than the chloramines. For solder, the rate of galvanic corrosion was only minimally influenced, while lead-free and tin-based solders were generally immune to chlorine attack.

In addition to ductile iron and PVC, materials such as copper and lead (used for piping) and brass (used for fixtures and connections) are used. Lead corrosion mechanisms include uniform corrosion and lead release. Copper corrosion mechanisms include uniform corrosion and copper release, localized-attack cold water pitting and hot water pitting, MIC, corrosion fatigue, and erosion-corrosion. Lead pipes and lead-tin solder exhibit uniform corrosion. Brass corrosion includes erosion-corrosion, impingement corrosion, dezincification, and stress corrosion cracking. The direct health impacts are due to increased copper, lead, and zinc concentrations in the drinking water. Mechanical problems due to corrosion include leaks from perforated pipes, the rupture of pipes, and the loss of water pressure due to the blockage of pipes by corrosion products. An example of a perforated copper plumbing pipe is shown in figure 2.

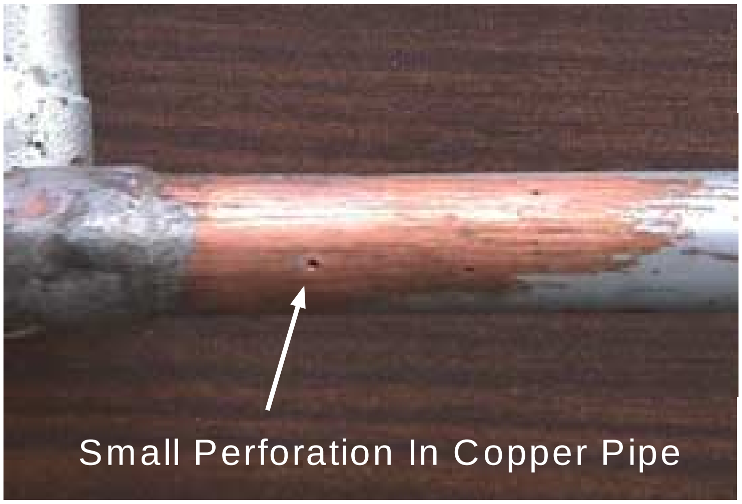

Figure 2. An example of a perforated copper plumbing pipe.

## Corrosion Issues Related to the Lead and Copper Rule

In 1991, the U.S. EPA implemented the Lead and Copper Rule (LCR). The LCR was developed to minimize health risks associated with the public's exposure to the lead and copper in drinking water. This regulation requires a treatment technique and uses an "action level" for lead of 15 parts per billion (ppb) (15 μg/L) at the 90th percentile. The "action level" for copper is 1,300 ppb (1,300 μg/L). The action levels constitute the maximum allowable concentrations, beyond which a response is required. The type of response depends on the size of the system. Guidance and detailed interpretations of the rule are found in various documents.(31-33)

## Corrosion of Lead Pipes and Solder Containing Lead

Lead is unusual among drinking water contaminants in that it seldom occurs naturally in water supplies such as rivers and lakes. The lead concentration in drinking water leaving water treatment plants is below the level of detection; however, lead can enter the water by corrosion or wear (erosion) of household brass fixtures, lead pipes, or lead solder. When water resides in plumbing more than 6 hours, testing has shown that lead levels can exceed the EPA action level of 15 ppb (15 μg/L) in some homes. Cold water lines usually have lower lead concentrations than hot water lines. Laboratory studies with lead pipe in the presence of corrosion inhibitors show that treatment of water with chemicals such as orthophosphate can aid in controlling lead leaching.(34) If the lead concentrations are too high, an alternative control method is to replace the home plumbing with new (copper) pipes.

## Corrosion of Copper Pipes and Fixtures

Since World War II, copper has been the most common material for consumer plumbing because of its excellent characteristics, including ease of installation, low cost, and corrosion resistance. Copper accounts for 50 to 90 percent of all tubes installed in drinking water services in industrialized countries.(35) In the United States, this amounts to well over 160 million m (500 million linear ft) of copper water tubing installed each year. Copper tubing has progressively displaced alternative materials for pipe sizes that are up to about 50 mm (2 in) in diameter, at which it is competitively priced. The wall thickness of copper tubing is usually 1 mm (0.04 in) or greater in the lower range of diameters. Corrosion problems, although infrequent, can be severe for the affected consumers and systems. Failure of copper tubing by pitting, blue or green water problems, and, more recently, failure to meet the U.S. EPA action level for copper in tap water samples are major problems when they occur. Table 12 summarizes the occurrence of different corrosion mechanisms for copper pipes, as reported for the United States, by the AWWA Research Foundation.(20)

Table 12. Frequency of copper plumbing system failures, as a function of failure causes, reported in the United States in 1983.(10)

| CAUSE OF COPPER TUBINGE FAILURE | FREQUENCY (%) |
|---|---|
| Pitting Corrosion | 58 |
| Erosion-Corrosion | 24 |
| Corrosion of Outer Surface Of Tubes | 7 |
| Faulty Workmanship | 5 |
| Fatigue | 2 |
| Other | 4 |
| **TOTAL** | **100%** |

Corrosion control methods for copper corrosion include prevention by improved production techniques that give better cleanliness of the inner bore, removing carbon films that are said to initiate pitting. The predominant practice is to use iron grit as a blasting material to clean the inner bore. This process reduced the frequency of severe cases of pitting by 90 percent or more. Another option for an improved production technique is to preoxidize the inner bore, which removes any carbon present and produces an oxide scale that is said to improve corrosion resistance. Once the pipe is in place, chemical treatment of the water supply is a method used to reduce the corrosive attack on copper pipes.

## Corrosion of Other Nonferrous Alloys

Nonferrous alloys are commonly used in domestic plumbing systems, either as fixtures, fittings, or in the making of joints. These alloys have been identified as a source of lead contamination in drinking water. Other chemical alloy elements of concern include copper, tin, zinc, antimony, and bismuth. The corrosion mechanisms vary greatly for each different alloy system and it is generally known that the local water composition influences the corrosion susceptibility of different alloys. Corrosion control methods for nonferrous alloys include preventive measures such as replacement of fixtures or a complete change of material design. In general, corrosion of nonferrous alloys is minimized by requiring plumbers to use industry-standard materials and workmanship when installing copper tubing systems.

## Requirements to Perform Corrosion Control Studies

Under the Lead and Copper Rule, operators of most large systems are required to chemically analyze their water and conduct a corrosion control study to determine an "optimal" strategy for reducing lead release rates. Corrosion testing often consists of two distinct parts, including the environment (in this case, water) and a variety of materials in contact with the water. Table 13 lists some estimated costs of common laboratory testing of drinking water, as it relates to corrosion.

Table 13. Common laboratory testing of drinking water related to corrosion and estimated cost per test, based on utility data from Columbus, OH.(18)

| TEST | COST / TEST |
|---|---|
| Weight Loss | $30 |
| Total Metals Concentration | $20 |
| Cation Concentration | $36 |
| Anion Concentration | $36 |
| Alkalinity | $12 |
| Hardness | $10 |
| pH | $5 |
| Chlorine Concentration | $15 |

Documenting the internal condition of pipes can be performed through visual inspection, photomicrographs, weight loss measurements, pitting potential measurements, scale analysis, and corrosion probe data.(36) Predictions of corrosion rates for future water quality conditions can be obtained through pilot studies. Pilot tests can then be compared with field tests and used to estimate the service life of pipes.

Many utilities use metal release tests to measure the interactions of their treated water with different materials. Metal release tests (sometimes referred to as metal uptake tests) are designed to measure the accumulation of corrosion products in water flowing through a plumbing system or a distribution network. In its guidance manual on corrosion control studies, the U.S. EPA emphasizes the use of large pipe loops as both analytic and operational tools to evaluate release rates and select an appropriate control strategy. There are two basic systems in use: a closed loop system and a recirculation loop system. When used in a recirculating closed loop system, the metal release measurement can be interpreted as a point estimate of the corrosion rate. More commonly, metal release measurements support a pipe loop corrosion control demonstration study, where the intent is to simulate a residential plumbing system and evaluate the metal concentrations experienced at the consumer's tap under different corrosion control strategies. An important problem to focus on when determining lead levels is the protocol for sampling the water to determine the lead level. Stagnation time, flushing, and the specific conditions of the installation under consideration have an important influence on the results, while the measurement of the corrosion rate of lead is a relatively minor concern.

### Corrosion Control in Sewage Water Systems

Sewage water is transported back to treatment facilities through a sewer water piping system that is connected to, but separate from, the drinking water system. The National Center for Environmental Research and Quality Assurance (The Office of Research and Development, U.S. EPA) reports that the current U.S. investment in sewage lines alone approaches $1.8 trillion.(37) Waste water is collected through relatively small-diameter pipes from bathrooms, kitchens, and sinks from each house and business and is then transported to treatment plants through larger diameter pipes. Rainwater will only enter the sewer system if it is collected through sewage grates collecting run-off water from streets and parking lots. All other rainwater and water used for activities such as watering a lawn or washing a car are simply absorbed by the earth, and do not run into the sewage system. Common materials of construction for sewage water systems include concrete piping, steel piping, and ductile iron piping.

The mechanisms of material degradation in sewage piping are generally similar to those in potable water systems. However, internal corrosion may be more severe because the water is not clean. In addition to the sewage waste, chlorine from salt winterizing treatments of roads comes into contact with the pipes. Cement-based piping deteriorates by corrosion of the reinforcement steel. The corrosion control method most commonly used in sewage piping is increased wall thickness. This is true for metal pipes and cement-based pipes. The thicker wall provides for a larger corrosion tolerance and, generally, a longer design life.

## CORROSION MANAGEMENT

### Corrosion Cost Estimates

The AWWA developed a six-step procedure for the assessment and control of internal corrosion of water distribution systems.(20) Figure 3 shows a flowchart illustrating the application of this method for internal corrosion.

Although the application of this method appears straightforward, working out the details for each system is quite complex. The procedure applies to older systems and does not consider corrosion prevention for new systems. It assumes that corrosion is already present and that the corrosion only occurs internally. Although the costs per system can be calculated reasonably accurately using this method, interactions with other systems are difficult to evaluate.

The system size, location, population served, materials used, water quality, and soil conditions all significantly influence corrosion susceptibility. The appropriate preventive strategies for corrosion control depend on the assessment of the local situations, options available to the local operators, available budgets (usually limited), and time frames.

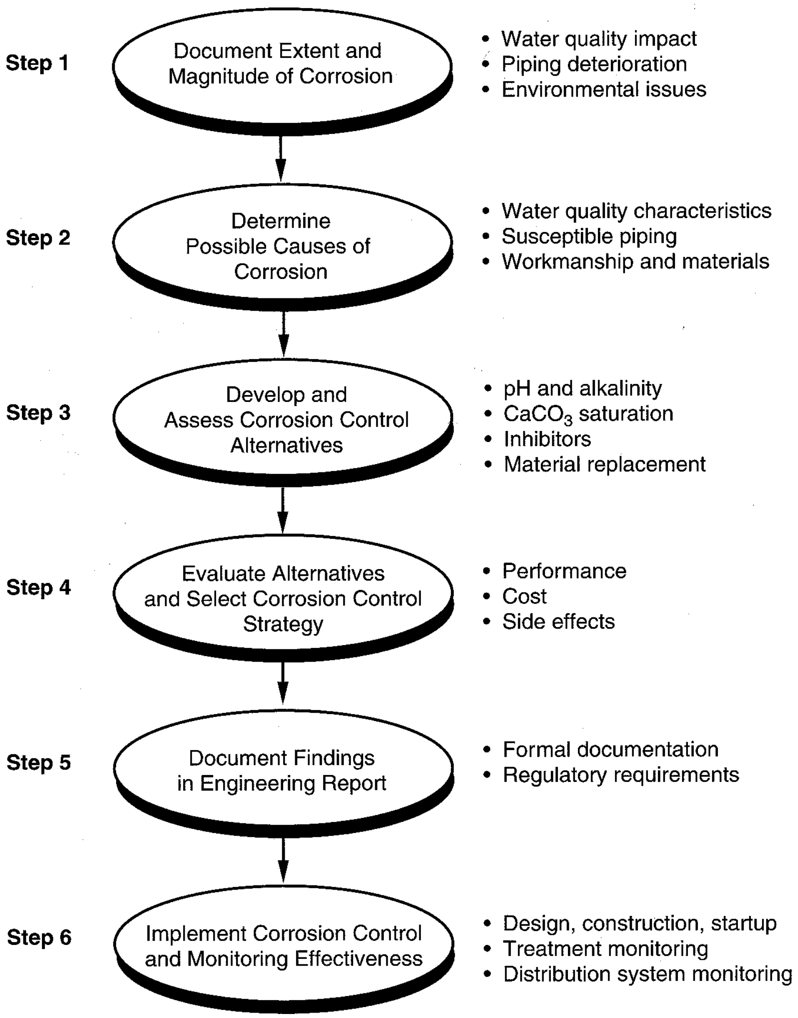

Figure 3. Corrosion control program implementation flowchart for internal corrosion.(20)

In 1993, Harrington(38) reported on methods to manage a corrosion control program. He presented 1992 to 1993 data showing a breakdown of water system leak repair costs and the resultant cost per average repair for the Marin Municipal Water District in California (see figure 4). For this chart, a total of 420 leaks were analyzed at an average repair cost of $3,640 per leak.

This figure shows that the direct costs of maintenance and repair ($724,000) and paving ($150,000) were roughly 57 percent of the total costs. The indirect costs of vehicles ($232,000), overhead ($211,000), and other indirect costs ($209,000) were roughly 43 percent of the total costs.

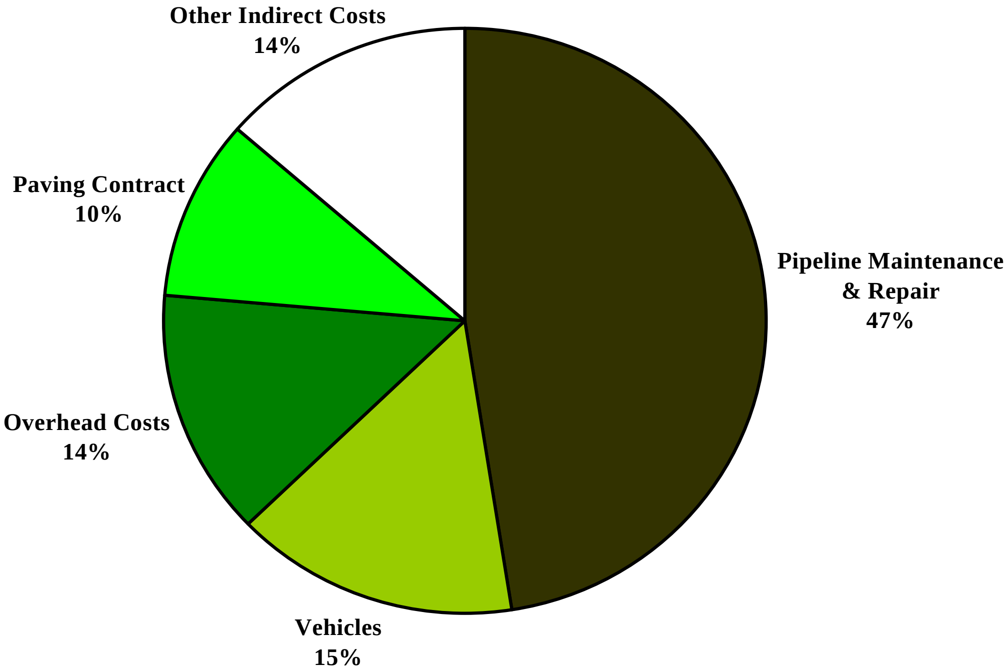

Figure 4. Pipeline repair costs for Marin Municipal Water District from 1992 to 1993, as reported by Harrington.(38)

## Short-Term Corrosion Management

Short-term corrosion problems are often indicated by customer complaints, such as the occurrence of red or yellow "rusty" water, or a sudden decrease in water pressure. A reason for rust-colored water is generally the presence of corrosion products that have flaked off of the internal pipe walls, while a water pressure drop may be caused by a leak in the transmission or distribution system. Finding a leak in an underground pipeline is often difficult because the leak may start small and go undetected for a period of time. Once the leak is so severe that water is literally coming from the ground, it may cause a local flood. In addition to the lost water, the damage can be significant and the repair work is more than what would have been needed to fix a small leak. In cases where a leak occurs below a street, a large sinkhole may form due to the sand rinsing away from underneath the asphalt, posing an additional safety hazard.

## Long-Term Corrosion Management

Long-term corrosion impact is generally indicated by integrity studies. Maintenance and inspection teams are dedicated to finding leaks and failures. Many utilities apply a specialized corrosion team to continuously monitor the water quality, using corrosion loops in which treated water circulates over weight loss coupons. The coupons are made from different materials, and they are exposed to various water flow rates. Periodically, these coupons are measured and average corrosion rates are determined. In addition to the weight loss coupons, water samples are routinely tested to ensure that the water quality is acceptable. The test results are used to make assessments about corrosion as well. For example, the pH of the water is important both for water consumers and for system integrity. The pH is kept within a predetermined range by adding pH adjusters to the treatment process. Dedicated corrosion groups mainly focus on corrosion prevention. They generally work with a fixed annual budget (a percentage of the total water utility budget).

## Keeping Corrosion Data Records

The corrosion groups are also in charge of keeping records on the number and type of failures that occur in a system. The data are used to assess when maintenance or replacement is needed. An example of a rule of thumb used by some planners is that a water line is completely replaced if three failures occur in 1 year within one block. Otherwise, the pipe is repaired and will remain in place.

Although information on individual repairs may be collected, in the current research, it was found that most water utilities do not have complete records on all their buried pipes. The pipe mileage length, pipe materials, pipe diameters, and installation dates are, in many cases, unknown. In many cases, this information is missing because of the age of the systems and the changes in the organization over the years. The lack of complete up-to-date information about all water systems complicates the process of prioritizing maintenance and the assessments for corrosion protection. The fact that computers have become commonplace in recent years provides the opportunity to maintain records in local databases and in a national database.

## Necessity of Long-Term Corrosion Planning

Because of the long life expectancy of water systems, a long-term vision for corrosion management is required. Unfortunately, some managers give in to short-term cost-savings over long-term investments. As an example, the average thickness of cast iron and ductile iron pipe has been continuously decreased over the last 100 years because thinner, higher strength pipe has become available. Clift(28) compared the change in wall thickness for 91.4-cm- (36-in-) diameter cast iron and ductile iron pipe, according to the AWWA specifications (see figure 5). These specifications showed that this thickness has been continuously reduced from 40 mm (1.58 in) in 1908 to about 9.7 mm (0.38 in) in 1991. Further reductions are due to service allowance, casting tolerance, and additional tolerance.

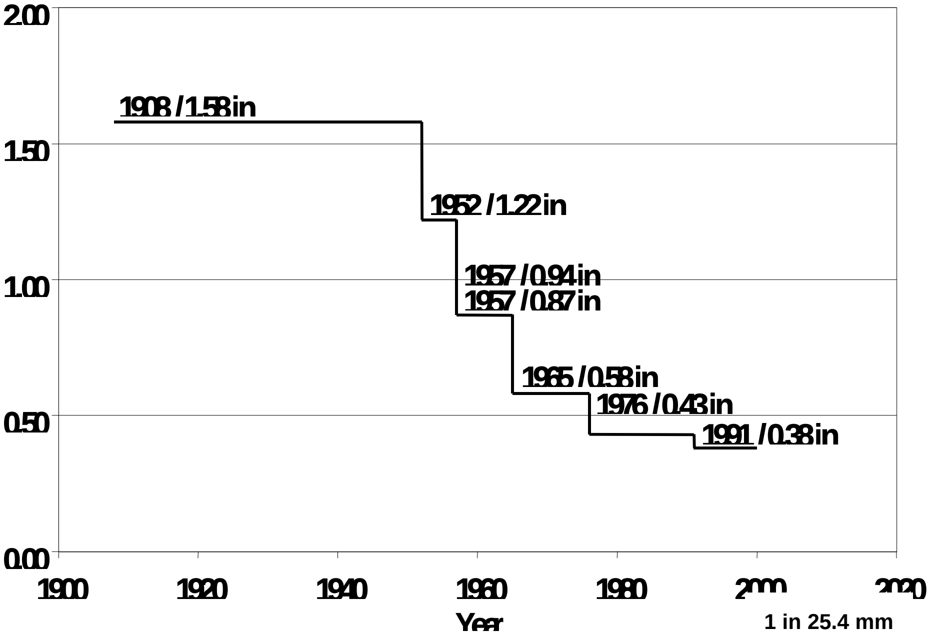

Figure 5. Actual size of AWWA specification thickness reductions for 0.925-m- (36-in-) diameter cast and ductile iron pipe, for 1.0 Mpa (150 psi) operating pressure, from 1908 to present.(28)

Unfortunately, corrosion rates are not significantly dependent on the strength of ductile iron or steel. As a result, thinner wall pipe will have a smaller corrosion tolerance than thicker wall pipe and will show more frequent failures. The failures cause high repair costs and inconveniences to the public. Extensive corrosion studies of buried pipe sections at more than 150 sites nationwide have shown that all ferrous pipe materials (including welded carbon steel pipes, cast iron, ductile iron, and wrought iron) corrode at approximately the same rate, assuming that general corrosion is the dominant mechanism.(39) The time to corrode through a pipe wall is directly proportional to the square of the wall thickness. That means that if the pipe wall thickness is reduced by 50 percent, the corrosion life will be reduced to 25 percent of the life of the original pipe thickness.

Although thicker wall pipe is more expensive, this method may be more cost-effective because it can prevent future customer complaints, unaccounted-for water through leaks, the need for continuous maintenance and inspection, and a lot of paper work for scheduling and reporting repair work. The use of thinner wall pipes requires additional corrosion protection in the form of coatings and cathodic protection (CP). In addition, the pipe sections must be bonded to be electrically continuous so that the CP will be effective.

## Optimized Management by Combining Corrosion Control Methods

Increased wall thickness is one effective way of decreasing corrosion impact. Table 14 shows a summary of the most commonly used repair methods for water systems with corrosion damage. They include the addition of corrosion inhibitors, pH adjusters, alkalinity controllers, and hardness controllers to the water; the application of cathodic protection; internal coatings and linings; internal inspection; external coatings; and the application of monitoring systems such as corrosion coupons, test stations, and corrosion data loggers. To prevent any further problems in cases where lead and copper release is a concern, one may consider the complete replacement of the tubes, fittings, fixtures, and joints by corrosion-resistant components.

Table 14. Summary of most commonly used repair methods for water systems with corrosion damage.

| WATER SYSTEM | DAMAGE | REPAIR METHOD |
|---|---|---|
| Any System | Small Corrosion Area or General Corrosion Over Large Area | Evaluate Structural Integrity<br>If Fit for Service, Then<br>Apply Coating to Protect Metal and<br>Inspect According to Appropriate Schedule |
| | Localized Corrosion | Identify Root Cause of Localized Corrosion<br>Remove Materials Causing the Corrosion<br>Replace Damaged Material |
| Wall of Dam or Storage Tank | Wall Thinning | Evaluate Structural Integrity<br>If Necessary, Reinforce Wall With Extra Steel |
| Metal Pipe | Small Leak | Clamp or Sleeve Around Pipe, or Replace Small Pipe Section |
| | Multiple Leaks | Replace Pipe Section |
| | Large Leak / Rupture | Replace Pipe Section |
| | Internal Corrosion | Apply Cement Lining |
| | | Insert PVC Tubing in Pipe |
| | External Corrosion | Evaluate Structural Integrity<br>If Fit for Service, Then<br>Apply Coating to Protect Metal, and/or<br>Apply Cathodic Protection To<br>Reduce Corrosion Rate |
| Cement-Based Pipe | Reinforcement Corrosion | If Localized, Remove Loose Concrete, Re-Apply |

Every system has its own requirements depending on the local conditions of the water (internal) and soils (external); therefore, a combination of the above-mentioned corrosion control methods must be carefully selected and consistently applied. Water line integrity managers should evaluate the effectiveness of the chosen mitigation program. Methods to check this include water sample measurements and evaluation of weight loss coupons, thorough review of customer complaints, and assessment of the reasons for unaccounted-for water.

The potential impact of failing systems should not be ignored. Large populations can be affected by a shortage in water supply. Prioritizing maintenance should be performed based on factors for each specific system, including the size of the population served, the location in rural or urban areas, the size of the system (large, medium, or small), the water quantity handled by that system, and the local water quality, which can be a function of seasonal activity.

## CHANGES FROM 1975 TO 2000

### Changed Need for Water Quantity

The changes in water systems can be summarized by recognizing the need for continuously increasing water quantity and continued concern regarding the impact of water quality on health. Water systems have very long design lives, typically 100 years or more, which relate to average replacement rates of 1 percent per year; therefore, the 25-year time period for water systems should be expanded to a longer time. Water utilities emphasize that a long-term view (20 to 50 years) for water supply is required for optimized maintenance.

One of the most significant changes is the growth in the U.S. population in the last 25 years and the anticipated continued growth into the future. In some areas of the country, the water supply is already strained. The capacity of water treatment, storage, transmission, and distribution will continue to increase. The interconnectivity of larger systems will provide the extra capacity needed during times of increased demand. Many cities have action plans in case of droughts, in which citizens are asked to limit their water usage. For example, during a drought, citizens are often encouraged to refrain from watering lawns and washing cars.

### Changed Need for Water Quality

The second most significant change is in the increased awareness of water quality and the lower tolerance limits in water quality standards. The efforts made since the early 1970s to clean up environmental pollution to ensure safe water from surface water and groundwater sources are paying off. Ten years after the Lead and Copper Rule took effect, the actual achieved results are becoming visible. Comparison of U.S. rules and regulations with those of other industrialized nations and the results of international studies may direct the course of future actions. A concern of water utilities is the uncertainty around future requirements and regulations by the U.S. EPA and the federal government. Water managers are confronted with the task of optimizing the use of aging systems and system reliability, both of which are of the utmost importance to water suppliers and their customers. Each system requires the careful selection of one or more corrosion mitigation methods to ensure its continued operation. Changes in regulations make future financial planning for construction and maintenance a difficult job.

## CASE STUDIES

### Case Study 1. City of Columbus, Ohio – Analysis of Water Line Breaks

As an example of the manner in which a water utility can analyze its maintenance practises, the *1997 Operations Report* of the Division of Water, of the City of Columbus, Ohio, was investigated.(18)

Figure 6 shows the percentage of unaccounted-for water in Columbus, Ohio based on 25 years of record-keeping. The figure shows that the direct economic impact to the water utility is 20 percent less revenue. For 1997, the total water pumped to the city was 184 million $m^3$ (48.5 billion gal), while only 146 million $m^3$ [38.6 billion gal (79.4 percent)] were metered. To the customers, this means higher water prices in order to make up for the loss. In addition, the enormous effort of treating all this lost water is wasted by the unidentified leaks.

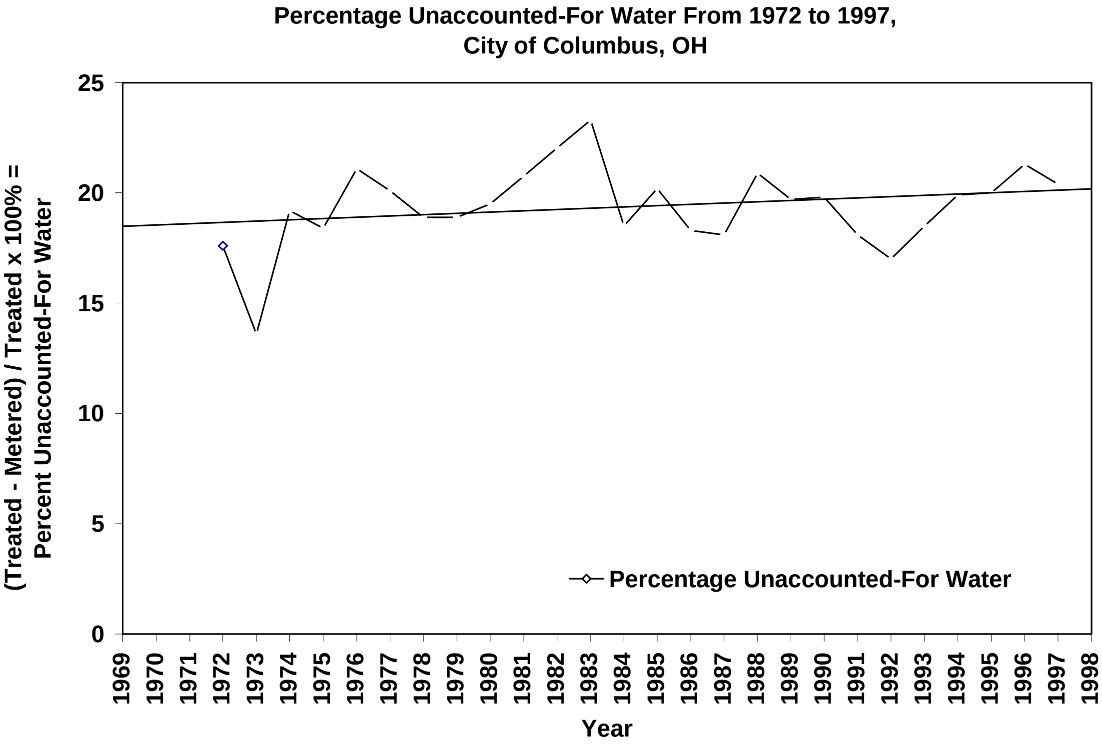

Figure 6. Percentage unaccounted-for water from 1972 to 1997 for the city of Columbus, OH.(18)

The city of Columbus, with approximately 1 million inhabitants, averages 500 to 800 significant water pipe breaks each year. Figure 7 shows that during the last 25 years, the number of line breaks is consistently rising. This increase in the annual number of main line breaks can most likely be attributed to the system's increasing size and age. Although Columbus consistently fixes these leaks at an approximate total annual cost of $9 million, the percentage of unaccounted-for water did not decrease during the last 25 years. If the leaks are detected and fixed earlier, the capacity of treatment facilities could be considerably smaller, contributing to greater efficiency and extra profitability for the system.

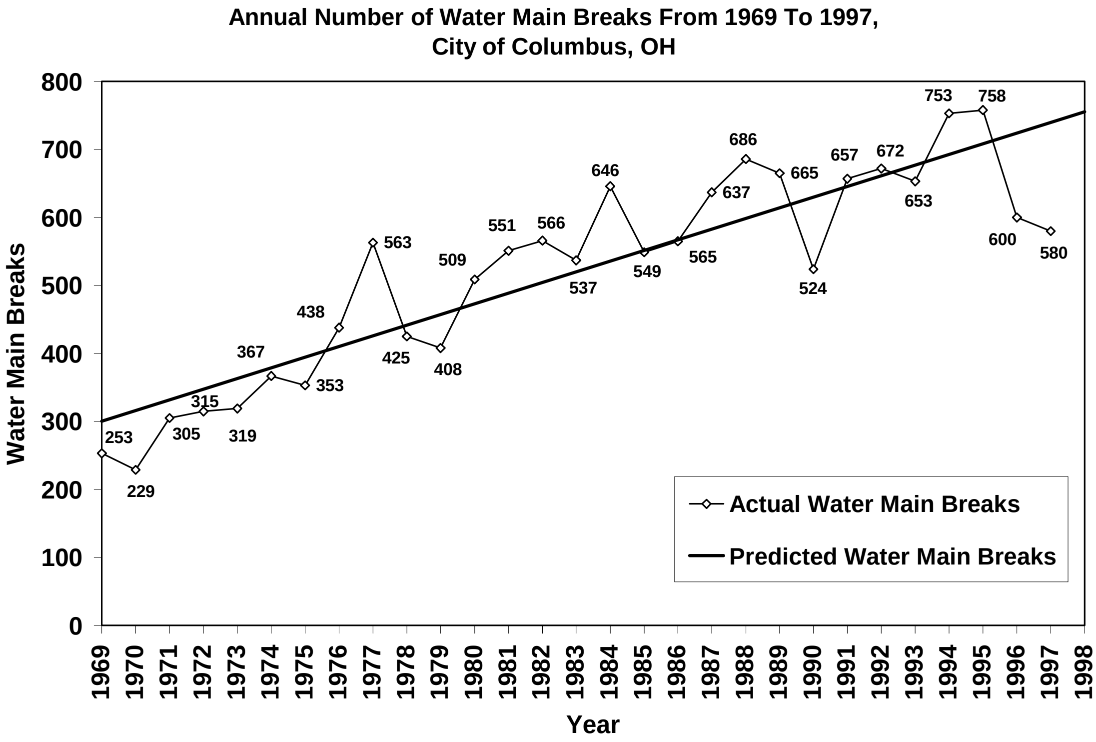

Figure 7. Number of actual and predicted water main breaks from 1969 to 1997 for the city of Columbus, OH.(18)

Tables 15a through 15d show analyses of the main line breaks that occurred in 1997, arranged by type of break, pipe materials age of pipe, and monthly distribution, respectively. Although the causes of leaks may be internal or external corrosion or, in general terms, “system aging,” they are usually not strictly reported as such. However, a crack across a pipe, a split along a pipe, or a pit or hole in a pipe usually has corrosion as its cause. For example, a crack in a pipe that appears to be caused by soil movement would probably not have occurred if there was no wall loss from corrosion at that location.

Table 15a shows that 518 of the 580 breaks (89 percent) could be directly attributed to corrosion. Table 15b shows that 64 percent of these 580 breaks occurred on (gray) cast iron pipe, and another 29 percent occurred on galvanized pipe. Table 15c shows that the majority (78.8 percent) of the pipe breaks occurred on pipes that were between 30 and 75 years of age. The very old pipe category (> 75 years) shows a lower percentage of breaks because there is a lower percentage of such in the system. This table also indicates that for about 10 percent of the pipes, no data were available regarding their time of installation (age). Table 15d shows that the winter months have more water main breaks than the summer months. This is attributed to the external loads applied on the buried pipes when the surrounding soil freezes. A similar phenomenon occurs in the summer in states such as Texas and Arizona, where the soil loses a lot of its moisture. The external support soil around the buried pipes shifts due to the shrinking soil, resulting in an increased number of main line breaks in the summer months.

Table 15a. Type and number of water main breaks in 1997 for the city of Columbus, OH.(18)

| TYPE OF BREAKS | NUMBER OF BREAKS | FRACTION (%) |
|---|---|---|
| Cracked Across Pipe | 265 | 45.7 |
| Split Along Pipe | 80 | 13.8 |
| Pit or Hole in Pipe | 173 | 29.8 |
| Cracked at Corporate Stop | 2 | 0.3 |
| Fitting or Joint Leak | 44 | 7.6 |
| Man-Made | 5 | 0.9 |
| Off-Set | 3 | 0.5 |
| Cut & Plug | 8 | 1.4 |
| Miscellaneous | 0 | 0.0 |
| **TOTAL** | **580** | **100%** |

Table 15b. Pipe material and number of water main breaks in 1997 for the city of Columbus, OH.(18)

| PIPE MATERIAL | NUMBER OF BREAKS | FRACTION (%) |
|---|---|---|
| Cast Iron | 371 | 64.0 |
| Galvanized Steel | 170 | 29.3 |
| Lead | 1 | 0.2 |
| Ductile Iron | 19 | 3.3 |
| Copper | 4 | 0.7 |
| PVC | 12 | 2.1 |
| Concrete | 3 | 0.5 |
| **TOTAL** | **580** | **100%** |

Table 15c. Age of pipe and number of water main breaks in 1997 for the city of Columbus, OH.(36)

| AGE OF PIPE | NUMBER OF BREAKS | FRACTION (%) |
|---|---|---|
| 1-10 | 5 | 0.9 |
| 11-15 | 3 | 0.5 |
| 16-20 | 8 | 1.4 |
| 21-25 | 6 | 1.0 |
| 26-30 | 19 | 3.3 |
| 31-40 | 108 | 18.6 |
| 41-50 | 224 | 38.6 |
| 51-75 | 125 | 21.6 |
| 76-100 | 16 | 2.8 |
| >100 | 6 | 1.0 |
| Unknown | 60 | 10.3 |
| **TOTAL** | **580** | **100%** |

Table 15d. Number of water main breaks per month in 1997 for the city of Columbus, OH.(23)

| MONTH | NUMBER OF BREAKS | FRACTION (%) |
|---|---|---|
| January | 119 | 20.5 |
| February | 55 | 9.5 |
| March | 25 | 4.3 |
| April | 34 | 5.9 |
| May | 25 | 4.3 |
| June | 35 | 6.0 |
| July | 34 | 5.9 |
| August | 35 | 6.0 |
| September | 30 | 5.2 |
| October | 47 | 8.1 |
| November | 71 | 12.2 |
| December | 70 | 12.1 |
| **TOTAL** | **580** | **100%** |

In 1997, the Columbus water department contracted with a third party to inspect large portions of their system for leaks. The survey covered 43 districts representing 1,720 km (1,069 mi) of pipeline. Seven of these districts were investigated further to locate the indicated leakage. The investigations resulted in the location of 69 leaks, the repair of which was projected to reduce system leakage by a total of about 8,328 $m^3$ per day (2.2 million gal per day) or about 3.0 million $m^3$ per year. This compares to about 1.65 percent of the 183 million $m^3$ (48.5 billion gal) annual total water pumpage, a savings of approximately $1.2 million, assuming an average consumer cost of about $0.40 per $m^3$ ($1.50 per 1,000 gal).

## Case Study 2. City of Cleveland, Ohio – Downtown Water Main Break

On Monday, January 12, 2000, at 5:45 p.m., a large water main rupture on East 9th Street in Cleveland, Ohio spilled 95 thousand $m^3$ (25 million gal) of water onto Cleveland's downtown streets. The flood spread quickly, covering a large area under a few feet of water. The 91.4-cm-(36-in-) diameter cast iron pipe, originally constructed in 1913, was buried 1.8 m (6 ft) underground. It burst on a road that runs between two of the city's best-known landmarks, the Rock and Roll Hall of Fame and Jacobs Field. The break created a crater 6 m (20 ft) in circumference and 1.8 m (6 ft) deep. It took approximately 3 hours for workers to bring the break under control and 5 days to completely repair the failure. The rupture made headlines in the local news for several days.(40)

The rupture of the old water main caused major disruptions:

- Three cars were stuck in the water, which was up to 0.6 m (2 ft). The motorists were able to leave their cars safely, and one was able to drive his away after the flood.
- Rush-hour traffic was affected. Fire and police officials closed down part of East 9th Street.
- All Cleveland public and parochial schools, as well as Cleveland State University, were temporarily closed because of the break. The school district has 76,000 students.
- More than 70 businesses were affected, with one business owner estimating his losses at about $50,000. An owner of a pizzeria reported that his pizza couriers needed to pay more for parking farther away. A bakery owner reported that only half as many customers came to his store.

- People who live downtown and in several adjacent neighborhoods were forced to boil their drinking water as a precautionary measure.
- Emergency rooms at two hospitals had to turn away some people who were seeking medical attention. Hospital personnel were trying to preserve water for patients who had already been admitted.
- As the water receded, it left a muddy mess along East 9th Street. By 10 p.m., front-end loaders were removing mud and other debris from the road.
- Water and electric power were affected in downtown office buildings near the line break.

NewsNet5(40) published a background article investigating the history of the Cleveland pipes. The current rupture was fixed by replacing a 4-m (12-ft) section; however, Cleveland has 8,000 km (5,000 mi) of underground water pipe, most of it between 80 and 100 years old.

The ruptured pipe was made of cast iron, which made it subject to tuberculation. The Public Services Director of Lakewood, a city adjacent to Cleveland, said that they systematically replace all old pipes, while Cleveland focuses on cleaning out old pipes and relining them with concrete. The Cleveland Water Commissioner said, “We spend $6 million a year on rehabilitating pipes. We feel that's more cost-effective than coming in, tearing up, and disrupting streets.” In both old pipes and new pipes, there is not a good way to predict where the next break is most likely to occur. Furthermore, just because a pipe is 90 years old does not mean that it is no good. Fluctuations in water pressure contribute to water main breaks. As long as the pressure is constant and the ground does not shift, the old pipes do very well. Shutting down all the lines affected by the break could mean more breaks in the future. Cleveland has spent a total of $1 billion over the past 20 years improving and rehabilitating the system, and that level of spending will continue.

## Case Study 3. City of Martinez, California – Impact of the Lead and Copper Rule

The impact of the Lead and Copper Rule can be illustrated using the case of the city of Martinez, California. In 1993, this city was surprised by the high lead levels measured during the first round of monitoring.(41) The rule permits water utilities to consider how certain measures to control corrosion will affect other regulated water quality parameters. All of the corrosion control options called for the addition of modified chemicals following filtration; thus, they would not interfere with the primary disinfection process. However, because all the options require altering the finished water's pH, residual disinfection could be affected. This would need to be monitored. The addition of zinc orthophosphate would cause problems in the intake feed (additional flushing required), in the wastewater treatment facilities (one using wetlands, one using a furnace), and for consumers (taste problems in the transition period). After considering all parameters, pH adjustment by a small increase in the existing sodium hydroxide levels seemed to cause the least problems and was also the least expensive.

## Case Study 4. City of Boulder, Colorado – Study of Nature and Extent of Corrosion

In 1982, a study was conducted for the city of Boulder, Colorado.(42) The purpose of the study was to evaluate the corrosion potential of the local water supply and analyze the extent of the corrosion problem throughout the distribution system. Water samples from the water treatment facilities and from a cross-section of homes in the city were collected and analyzed for the following corrosion-related parameters: pH, alkalinity, $CO_2$, chlorine, turbidity, temperature, calcium hardness, total dissolved solids, specific conductance, silica, dissolved oxygen, chloride and sulfate/alkalinity ratio, and color.

Metals were monitored to determine if their concentrations were sufficiently high to warrant concerns about health. Measured concentrations of metals were low in the water and were found to be within the EPA limits. Although the water is aggressive to the materials it contacts, the water quality was not shown to be a health risk. The results indicated that internal pipe corrosion was severe within Boulder and that two types of corrosion (general corrosion and pitting corrosion) were occurring. The cause of the internal corrosion was identified as insufficient concentrations of calcium and alkalinity, and the supersaturated levels of dissolved oxygen.

Investigations of corrosion-related parameters in drinking water are an important aid to water utilities. The appropriate action for improved corrosion control should be determined based on a complete review of the system and a thorough analysis of the data. Data from future monitoring of water quality and system conditions can then be compared with the baseline data. The data should also be used to re-evaluate the applied chemical treatment for corrosion protection at regular intervals to adjust the current corrosion practice to the best practice available for a specific system under changing conditions. Treating the water for internal corrosion protection by using corrosion inhibitors, pH adjustment, and alkalinity adjustment will result in a cost-savings due to improved system integrity.

## Case Study 5. County Sanitation Districts of Los Angeles County, California – Anaerobic Selector and Carbon Dioxide Stripping

This case study is based on a study performed by the Joint Water Pollution Control Plant of the County Sanitation Districts of Los Angeles County,(43) and published on the web site of the Water Environment Research Foundation.(44)

The District's Joint Water Pollution Control Plant operates a High-Purity Oxygen-Activated Sludge (HPOAS) system, which consists of four trains of 189 thousand $m^3$ per day (50 MGD) of capacity each. Each train has four stages, with three surface aerators in each stage. This plant is a regional sludge management facility in which the treatment consists of primary and secondary treatments via the HPOAS system, sludge thickening, digestion, co-generation, and dewatering, and has a total rated capacity of 1.46 million $m^3$ per day (385 MGD) and a current flow of 1.32 million $m^3$ per day (350 MGD). The plant staff observed two problems: bulking sludge and corrosion.

The plant had consistent problems with sludge bulking and foaming due to filamentous organisms such as nocardia. The Sludge Volume Index (SVI) generally ranged from 200 mL/g to 250 mL/g, with occasional excursions up to 300 mL/g. Sludge settleability problems forced the plant to operate at low Mixed-Liquor Suspended Solids (MLSS) concentrations and Mean Cell Residence Times (MCRT), which made the process vulnerable to shock loading. This is important since the facility is downstream from many major industries, including several refineries.

Another operating challenge of the HPOAS system was corrosion of structures and piping. The plant staff observed concrete deterioration amounting to approximately 6.4 mm (0.25 in) of concrete loss, a condition which became progressively worse from the second to the fourth stage. In addition, mild steel effluent piping and metallic chain-and-flight components in the secondary clarifiers appeared to be exhibiting accelerated corrosion. Plant staff attributed this corrosion to a low pH condition brought about by the progressive increase in partial pressure of carbon dioxide through the HPOAS head space. As the carbon dioxide concentration in the MLSS increased, carbonic acid was created, depressing the mixed-liquor pH and leading to deterioration of concrete and corrosion of steel surfaces. While the in-plant corrosion impacts could be addressed relatively simply, potential corrosion of the 12.9 km (8 mi) of unlined effluent tunnels and outfall structures by low-pH plant effluent was a serious concern when all plant wastewater would be treated through secondary treatment facilities.

Accordingly, the plant staff modified the HPOAS system to address these concerns. To reduce filamentous microorganisms in the MLSS, thereby improving the MLSS settleability, plant staff converted the first stage of the HPOAS reactors to an anaerobic selector, since literature indicated that anaerobic selectors produce a biomass that settles well. Conversion to an anaerobic selector was accomplished by intermittent operation of the first-stage aerators and a reduction of aerator blade sizes. By intermittently operating the three surface aerator, 2 hours per day each, excess solids deposition in the bottom of the first-stage reactors was avoided. Furthermore, plant staff cut the mixer blades of the first stage to shorter blade diameters to reduce the dissolution of oxygen into the MLSS.

To address the problem of corrosion (i.e., low pH), the plant staff investigated several alternative chemical methods for elevating the mixed-liquor pH. Unfortunately, a significant amount of chemicals would be required at a significant cost. They then investigated what level of carbon dioxide concentration would be allowable to significantly reduce the likelihood of corrosion. They determined that a pH of 6.7 was required, which corresponded to a dissolved carbon dioxide level of less than 100 mg/L. To achieve this carbon dioxide concentration, the districts then decided to investigate physical methods of carbon dioxide stripping, and selected air stripping since it was the most cost-effective technology. To test the feasibility of fourth-stage air stripping, the fourth-stage vents of the HPOAS reactors were opened and the reactor headspace was purged by airflow from a 595-$m^3$/min (21,000-$ft^3$/min) fan. Only the first three stages were operated with an elevated oxygen atmosphere, enabling the fourth stage of the reactor to function as a conventional air-activated sludge reactor. These modifications were incorporated in both existing facilities and in the design of new facilities that will double plant capacity. Implementing these modifications to the HPOAS system has had several benefits:

- selector modifications reduced SVIs to routinely less than 100 and virtually eliminated bulking and foaming,
- air-stripping modifications raised the secondary effluent pH from 6.2 to 6.7. At this level, it is projected that it would take 75 years to corrode the concrete tunnels and outfalls to the depth of the rebar, and
- air stripping saved a minimum of $2 million per year over potential chemical methods of pH elevation.

## REFERENCES

1. Safe Drinking Water Act Amendments, 42 USC 300j-15, 1996.

2. "Household End Use of Water Without and With Conservation," *1997 Residential Water Use Summary – Typical Single-Family Home*, American Water Works Association, WaterWiser Website.

3. W.B. Solley, R.R. Pierce, and H.A. Perlman, "Estimated Use of Water in the United States in 1995," *U.S. Geological Survey Circular 1200*, U.S. Department of the Interior, 1998.

4. Water Industry DataBase: Utility Profiles, Report by the American Water Works Association, AWWA, Denver, CO, 1992.

5. L.B. Staples, "New Tools for the Condition Evaluation of Waterlines," *1995 Conference on Corrosion and Infrastructure, Practical Applications and Case Histories*, NACE International and U.S. Department of Transportation, Federal Highway Administration, 1995.

6. *Drinking Water Infrastructure Needs Survey, First Report to Congress*, Publication No. EPA-812-R-97-001, U.S. Environmental Protection Agency, Office of Water, Office of Ground Water and Drinking Water Implementation and Assistance Division, Washington, D.C., January 1997.

7. D. Travers, Survey Manager of the U.S. Environmental Protection Agency, Office of Water, *Summary Data of the Drinking Water Data System Database* (in Electronic Format), Washington, D.C., Personal Communication, March 2000.

8. *Infrastructure Needs for the Public Water Supply Sector*, Stratus Consulting, Inc., Boulder, CO, December 1998.

9. *Clean and Safe Water for the 21st Century – A Renewed National Commitment to Water and Waste Water Infrastructure*, Water Infrastructure Network (WIN), 2000.

10. *Effects of Structural Changes in the U.S. Economy on the Use of Public Works Services, A Report to the National Council on Public Works Improvement*, U.S. Department of Commerce, Office of Business Analysis, 1987.

11. Benett et al., 1979, cited in R.A. Ryder, *JAWWA 72*, 1980, pp. 267-279.

12. C. Hahin, “Predicting the Metallic Corrosion Costs of Operating and Maintaining Buildings and Utility Systems,” *Materials Performance*, 1978, pp. 31-34.

13. R.M. Clark and J.A. Goodrich, “Developing a Data Base on Infrastructure Needs,” *JAWWA 81*, 1989, pp. 81-87,

14. *Survey of Operating and Financial Characteristics of Community Water Systems*,” U.S. Environmental Protection Agency, Washington, D.C., April 1977.

15. R.A. Dangel, *1975 Study of Corrosion Products in the Seattle Water Department Distribution System*, Report No. 670/2-75-036, U.S. EPA, Cincinnati, OH, 1975.

16. R. Levin, M.R. Schock, and R.M. Clark, “The Current State of Corrosion Control Technologies and Costs,” *Proceedings of Water Quality Technology Conference: Advances in Water Analysis and Treatment*”, AWWA, Philadelphia, PA, November 1989, pp. 575-604.

17. *Analysis of Sales of Treated Water Between Denver and Outside City – 1999*, Denver Water (Non-Accrual Basis), April 2000.

18. *1997 Operations Report*, Division of Water, City of Columbus, OH, Department of Public Utilities, 1997.

19. D.D. Rittman, *El Paso Water Utilities Selected Financial and Statistical Data – 10 Years*, El Paso Water Utilities Public Service Board, El Paso, TX, April 2000.

20. *Internal Corrosion of Water Distribution Systems*, 2nd Edition, Cooperative Research Report, American Water Works Association Research Foundation and DVGW-Technologiezentrum Wasser, Denver, CO, 1996.

21. S.J. Duranceau, M.J. Schiff, and G.E.C. Bell, *Effects of Electrical Grounding on Pipe Integrity and Shock Hazard*, Order Number 90702, AWWA Research Foundation, June 1996.

22. D.A. Lytle et al., “Using Aeration for Corrosion Control, *JAWWA*, Vol. 90, No. 3, March 1998, pp. 74-88.

23. I. Wagner, “Effect of Inhibitors on Corrosion Rate and Metal Uptake in Drinking Water Systems,” *Proceedings of Seminar on Internal Corrosion Control Developments and Research Needs*, AWWA, 1989, pp. 1-17.

24. W.E. Neuman, “AWWC Experience With Zinc Orthophosphate Treatment,*” Journal of the New England Water Works Association*, Vol. 109, No. 1, March 1995, pp. 57-60.

25. J.E. Singley, B.A. Beaudet, P.H. Markey, D.W. DeBerry, J.R. Kidwell, and D.A. Malish, “Corrosion Prevention and Control in Water Treatment and Supply Systems,” Chapter 9 – “Costs of Corrosion Control,” *Pollution Technology* Review, No. 122, Noyes Publications, Park Ridge, NJ, 1985.

26. W.C. Robinson, “Steel Storage Tanks Corrosion Control Methods,” Paper 522, Corrosion/91, NACE Annual Conference, Cincinnati, OH, 1991.

27. W.H. Cates, *History of Steel Water Pipes, Its Fabrication and Design Development*, 1971.

28. J.S. Clift, *Corrosion Protection for Water Transmission Pipe, A Practical Guide for Long-Term Performance*, Price Brothers Company, Dayton, OH, January 2000.

29. R.A. Ryder, "The Costs of Internal Corrosion in Water Systems," *JAWWA*, Vol. 72, No. 5, May 1980, pp. 267-279.

30. S. Reiber, *Chloramine Effects On Distribution System Materials*, Order No. 90624, AWWA Research Foundation, September 1993.

31. *Lead and Copper: A Working Explanation of the Lead and Copper Rule*, AWWA, Denver, CO, 1991.

32. *Lead and Copper Rule Guidance Manual, Vol. I: Monitoring*, U.S. EPA, Denver, CO, 1991.

33. *Lead and Copper Rule Guidance Manual, Vol. II: Corrosion Control and Treatment*, U.S. EPA, Denver, CO, 1992.

34. B.P. Boffardi and A.M. Sherondy, "Control of Lead Corrosion by Chemical Treatment," Paper 445, Corrosion/91, *NACE Annual Conference*, Cincinnati, OH, 1991.

35. A. Cohen, and J.R. Myers, "Mitigation of Copper Tube Cold Water Pitting by Water Treatment," Paper, Corrosion/84, *NACE Annual Conference*, 1984.

36. G.J. Kirmeyer, R. Donner, and R.A. Ryder, "Methods for Assessing Economic Impacts of Plumbing Corrosion," *Proceedings of AWWA Seminar on Water Quality Concerns in the Distribution System*, AWWA, Denver, CO, June 1986, pp. 109-119.

37. *Rehabilitation of Urban Infrastructure Systems*, National Center for Environmental Research (NCER), Office of Research and Development, U.S. Environmental Protection Agency, http://es.epa.gov/ncerqa/sbir/sbir97/rehab.html, December 2000.

38. T. Harrington, "Managing a Corrosion Control Program," *Proceedings of Distribution Systems Symposium*, AWWA, San Diego, CA, September 1993, pp. 53 – 64.

39. M. Romanoff, "Underground Corrosion," National Bureau of Standards Circular 579, April 1957.

40. NewsNet5, Associated Press, www.newsnet5.com/news/stories/news-20000113-205004.html, January 2000.

41. W.C. Pease and B.A. Henderson, "Coping With Unexpected High Lead Levels," *1993 Annual Conference Proceedings*, AWWA, Water Quality, San Antonio, TX, 1993, pp. 125-136.

42. J.M. Palecki Ray, *The Nature and Extent of Internal Corrosion Within the City of Boulder Water System*, Master of Science Thesis, Department of Civil, Environmental, and Architectural Engineering, University of Colorado, Boulder, CO, 1982.

43. R. Morton, County Sanitation Districts of Los Angeles County, Joint Water Pollution Control Plant, Carson, CA.

44. *Case Study: County Sanitation Districts of Los Angeles County (Calif.) Anaerobic Selector and Carbon Dioxide Stripping*, Water Environmental Research Foundation, www.werf.org/toolkit/process/los_angeles.html, December 2000.