A/C Pipe
Producers Association

Internal Correspondence

TO Board of Directors

FROM J. C. Jackson, President

DATE July 14, 1982

SUBJECT Determinants and Options for Water Distribution System Management: A Cost Evaluation

ACTION REQUIRED: Review and retention

As a supplement to TAC-01-82, Municipal Analysis Program, Summary Report I, enclosed for review and retention is a rather interesting treatise prepared by the U.S. Environmental Protection Agency entitled "Determinants and Options for Water Distribution System Management: A Cost Evaluation."

While based on a limited municipal data base and mainly applicable to cast iron distribution systems, the conclusions reached either were confirmed or inferred by the findings of the in-house municipal survey conducted by Wade Miller Associates, Inc.. Finally, the mathematical relationships derived may be of some value in assessing distribution system problems endemic to other locales.

JCJ/ajb

Enclosure

cc: A. Kahn, Esq.
W. Miller
International Affairs Committee

copies to: Board of Directors

L. Ambler
L. Cejudo
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W. Gallant
L. Taylor

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January 1982

DETERMINANTS AND OPTIONS FOR WATER DISTRIBUTION SYSTEM MANAGEMENT: A COST EVALUATION

by

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ABSTRACT

This report deals with the problems associated with maintaining and replacing water supply distribution systems. Some of these problems are associated with public health, economic and spatial development of the community, and costs of repair and replacement of system components. Statistical models are developed that demonstrate the relationship between population growth and development and growth of the water supply service network. A repair frequency analysis has been completed for distribution system maintenance events (leaks and breaks). The economic implication of various replacement strategies and the effect of water quality (corrosivity) on water loss and system cost are examined. This analysis is based on the data acquired from one large (260 mgd; 950,000 m^3/sec) and one smaller (20 mgd; 75000 m^3/sec) water utility.

The Capital facilities that make up urban service networks such as water supply delivery systems, sewage collection networks etc., are often called the urban infrastructure. The water system infrastructure represents a major investment for a municipality. Because of the potential public health and safety implications of an adequate water distribution system, maintaining this system in good condition is an extremely important responsibility for water utility management. As this study shows, once a length of a pipe begins to require maintenance, its maintenance rate increases exponentially. Maintenance costs soon exceed the costs of replacement. Therefore establishing a timely maintenance and replacement program is extremely important from an economic and public health viewpoint.

FOREWORD

The Environmental Protection Agency was created because of increasing public and governmental concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of the environment and interplay among its components require a concentrated and integrated attack on the problem.

Research and development is the first step in problem solution as it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems (1) to prevent, treat, and manage wastewater, solid and hazardous waste, and pollutant discharges from municipal and community sources, (2) to preserve and treat public drinking water supplies, and (3) to minimize the adverse economic, social, health and aesthetic effects of pollution. This publication is a product of that research and is a most vital communications link between the researcher and the user community.

Water supply service can be divided into the functions of acquisition, treatment, delivery, and support services. As exemplified by the Safe Drinking Water Act of 1974, most regulatory and professional interest has been placed on the treatment function because it represents the barrier between the user and potentially infectious disease and uncertain raw water quality. A factor frequently overlooked in dealing with water systems, however, is the effect that the delivery system can have on the quality of water received at the tap.

From an economic and social point-of-view, water distribution systems play a highly significant part in the total water supply responsibility. In general, water delivery systems account for over 85% of the cost associated with drinking water service. From a social point of view, the water delivery network plays a significant role in the spatial development and growth rate of a community.

In this report, an attempt is made to analyze the relationships that exist between spatial development and the urban water distribution infrastructure and the costs of repair and replacement associated with maintaining that infrastructure.

Francis T. Mayo, Director
Municipal Environmental Research Laboratory

ACKNOWLEDGEMENTS

The continuing cooperation of many people enabled the completion of this study. Particular acknowledgement should be given to the following individuals: Mr. George Cummings and Mr. Bob Johnson of Hamilton County and Boone-Kenton-Campbell Counties soil conservation services, for their assistance in defining soil types; Messers Jim Krusling, Bob Mayhan and Dave Rupe of the Cincinnati City Traffic Engineering Department and Mr. Steve Sorrell of the Hamilton County Engineering Department for their assistance in defining traffic variables that might influence pipe maintenance; Mr. Jim Dell of the National Weather Service who helped us acquire weather records for our analysis; Messers Jim Remmell, Jeff Earlywine and Ms Beth Wilkins, of the Northern Kentucky Area Planning Commission and Mr. Chip Block for their assistance in helping us organize our spatial data analysis; Dr. Jochen Kuhner, independent consultant, Dr. Tom Walski, and Mr. Christopher Hahin of the Army Corps of Engineers and Mr. David Mair, Chief Chemist, Water Research Laboratory, City of Columbus for their review and comments; Ms Marion Curry and Mrs. Susan Campbell for their assistance in preparing this manuscript.

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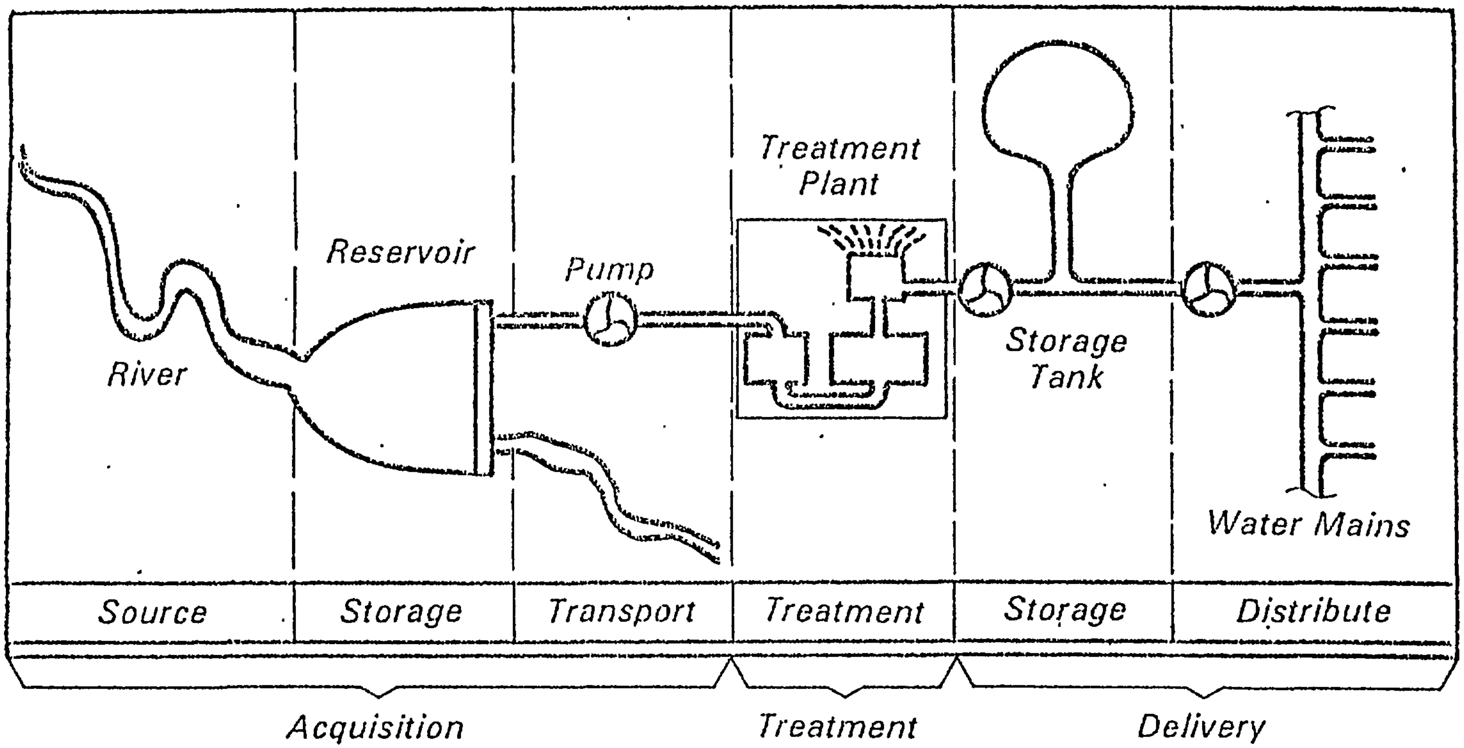

Figure 1. Schematic diagram of acquisition, treatment, and distribution functions for a typical water supply system.

INTRODUCTION

Approximately 213 million people are served by community water supply systems in the United States.[1] A community system, as defined by the Safe Drinking Water Act, is one that serves at least 15 service connections used by year-round residents or one that regularly serves at least 35 nonresidents. In addition to community systems, there are approximately 200,000 noncommunity water systems. Most of these are privately owned and are found at motels, restaurants, camp grounds, parks and other places frequented by the traveling public. The benefits of a safe, permanent water supply are obvious, but its existence is usually taken for granted, at least by the general public.

Water supply service can be divided into a series of functions: acquisition, treatment, and delivery (Figure 1). Most professional and regulatory attention has been focused on the treatment function because it represents the barrier between potentially infectious disease from uncertain raw water quality and the water user. A frequently overlooked factor in dealing with water systems, however, is the effect that the water delivery system can have on the quality of water received at the tap. After drinking water has passed through the treatment plant several mechanisms can introduce bacteria into drinking water:[2]

- open reservoirs;
- enclosed reservoirs to which chlorine is not added occasionally;
- new construction, which may disturb the existing system:
- main breaks, which may become an increasing problem as distribution systems age;
- cross connections improperly installed, which cause back siphonage and back pressure:
- dead ends in mains, which cause stagnate water; and
- living organisms in mains which when disturbed may release bacteria.

Maintenance of water quality in the distribution system is just as important as ensuring that safe water enters the system initially.

A family of four currently uses approximately 255 gallons (965 liters) of water each day. As can be seen from Table 1 less than 1% of this domestic use is directly for cooking and consumption, but 100% of the water must be maintained at very high standards because there is generally only one distribution system.[3] In addition to domestic use, water must also be available for fire protection, industrial use,

TABLE 2. AVERAGE ANNUAL DEPRECIATION COST IN DOLLARS*

Function	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979
Support Services	$359,000	$364,000	$374,000	$390,000	$398,000	$402,000	$407,000	$406,000	$410,000	$419,000
Acquisition	82,000	83,000	85,000	89,000	91,000	91,000	92,000	92,000	93,000	95,000
Treatment	180,000	182,000	187,000	195,000	199,000	201,000	203,000	203,000	205,000	210,000
Delivery	1,012,000	1,027,000	1,054,000	1,099,000	1,122,000	1,134,999	1,146,000	1,145,000	1,156,000	1,182,000
Total	1,633,000	1,656,000	1,700,000	1,773,000	1,810,000	1,828,000	1,848,000	1,846,000	1,864,000	1,906,000

*Depreciation is calculated by dividing the initial cost by design life.

and irrigation. Water utilities, therefore have a significant responsibility that goes beyond the supply of potable water.

TABLE 1. WATER CONSUMPTION BY CATEGORY

Use	Percentage of Total
toilet	39
bathing	31
laundry	14
dishwater	6
kitchen sink	5
lavatory	3
utility sink	2
consumption	less than 1

The treatment and delivery functions of a water utility represent large economic investments. The relative capital costs of the various water system functions, based on the acquisition, treatment, delivery, and support services categories for a typical municipal water supply can be compared (Table 2).[4] Support services, as used here represent the management and administrative functions of the water utility. As can be seen, the bulk of the expenditures are in the delivery system. The absolute magnitude of this expenditure can be illustrated from data taken at a large midwestern water utility approximately 260 MGD (950,000 m^3/day) capacity which will be examined more carefully in later sections. The replacement value of the delivery system (not including treatment, acquisition and support services) is estimated at $917,814,700 based on current dollar/foot rates (1978). Maintenance of the delivery system in 1978, cost approximately $2,600,000 per year.

From the previous discussion the water utility delivery system obviously represents a large and important portion of the water utility's budget. The delivery system also has a significant role to play in terms of community public health. Another often unmentioned role that a water utility plays is in community development. Planning for water supply is a complex process that involves a number of entities within any community. The provision of water supply services has had and

TABLE 3. PERCENT OF TOTAL O&M COSTS FOR 10 LARGE UTILITIES FOR FOUR STANDARD FUNCTIONS

	Year						
Function	1972	1973	1974	1975	1976	1977	1978
Support Services	27.98	26.58	27.89	25.80	24.08	26.45	27.79
Acquisition	12.71	11.81	13.77	13.62	12.71	13.35	12.58
Treatment	21.31	20.13	20.65	22.57	25.23	21.14	20.39
Delivery	37.98	41.48	37.69	38.01	37.98	39.06	39.24

TABLE 4. DATE OF FIRST PIPE INSTALLATION FOR SELECTED UTILITIES[5]

Utility	Date of First Installation
Manchester, NH	1874
Passaic Valley, NJ	1899
Duluth, MN	1898
Lake Zurich, IL	1915
Kansas City, MO	1880
Dallas, TX	1876
San Diego, CA	1890
Phoenix, AZ	1888
Orlando, FL	1900
Pueblo, CO	1875
Cincinnati, OH	1856
Kenton County, KY	1898

will continue to have a significant impact upon land use and development, particularly at the urban fringe. If expansion of a distribution system is planned and directed, this planned expansion can become a major tool for land use control within the community. If water facilities expand in a manner that is not coordinated with other planning efforts of the community the location of water facilities can become a determinant of the community's growth path. At the urban fringe, once water supply has been provided, controlling the rate and nature of development within the service area is difficult, if not impossible.

In this report an attempt will be made to deal with two major issues related to water supply systems. The first is the interaction between land use and development of water supply system development and the second is the cost and frequency of water system network replacement.

CHARACTERISTICS OF THE DISTRIBUTION SYSTEM

Obviously delivery systems involve a large capital investment as well as high annual replacement and repair expenses. Evidence is mounting that this annual investment is increasing over time in real dollars. Table 3 shows the percent of dollars spent on the four standard functions for a selected sample of water utilities in the United States for a 7-year period. The delivery category increased as a percent of total operations and maintenance costs and the increase is most likely the result of aging systems. To reinforce this idea, Table 4 lists some of the first installation dates for some selected (not the same) water utilities.[5] Most of these systems installed their first pipes in the late 1800's or early 1900's. Many of the distribution systems may be approaching an age when system breakage is increasingly prevalent, and these systems are not necessarily old compared to Boston, Philadelphia, and so forth.

TABLE 6. PARAMETERS OF DISTRIBUTION SYSTEM DESIGN[6]

	Physical Design Consideration
Basic land use/ demographic parameters	Service area Land use, densities Population growth
Natural features	Topography (slopes) soil types, water table
Capacity requirements	Per capita flow Peak-to-average flow
Engineering design criteria	1. Pipe characteristics: Manning's n 2. Joint materials 3. Minimum pipe diameter 4. Minimum velocity 5. Maximum velocity 6. Minimum and maximum slopes

With growing concern over available resources and the cost of energy and increasing societal awareness over the role of urban service systems in urban development, there is also greater awareness of the role water systems play in population growth. Such questions as, "Does population growth force growth in water supply systems?" or "Does availability of water service affect the quantity and direction of population growth in an urban area?" must be asked. Because of the health, social and economic functions served by water utilities, examining the economics of the repair, replacement, and maintenance of delivery systems is worthwhile. In this report the following issues will be examined: (1) spatial, demographic, and developmental implications of water system expansion; (2) an analysis of main break patterns and their economic consequences; and (3) a general investigation of the effect of water quality on water loss.

The first two issues are studied in the framework of a case study. The last issue is examined in terms of a cross-sectional study.

Table 5 shows the breaks per mile of the pipe contained in the annual reports for a nine year period for the large case study utility. As can be seen, the trend in breaks per mile is generally increasing over time.

TABLE 5. BREAKS PER MILE

	1970	1971	1972	1973	1974	1975	1976	1977	1978
miles in system	3702	3717	3758	3785	3812	3834	3852	3866	3887
(km)	(5957)	(5981)	(6047)	(6090)	(6134)	(6169)	(6198)	(6220)	(6254)
main breaks	604	738	592	735	749	982	1195	1113	723
breaks/mile	0.16	0.20	0.16	0.19	0.20	0.26	0.31	0.29	0.19
(breaks/km)	(0.10)	(0.12)	(0.10)	(0.12)	(0.12)	(0.16)	(0.19)	(0.18)	(0.12)
abandoned mileage/yr	1.22	3.35	2.44	2.96	4.12	4.12	4.35	0.28	3.20
(km/yr)	(1.96)	(5.39)	(3.93)	(4.76)	(6.63)	(6.36)	(2.14)	(0.45)	(5.15)

Design of water distribution systems can be divided into four major areas.[6] The first is concerned with basic land use and demographic parameters used to determine the preliminary size and shape of the service area. The second area of concern reflects the natural features. The third area of concern is the capacity requirement of the system as a whole and that of individual components. The fourth area of concern is that of engineering design criteria, such as the diameter of pipe, the minimum and maximum velocities, minimum and maximum slopes, and the flow characteristics of the pipes themselves. Table 6 summarizes these major areas of consideration.

Water supply distribution systems also play an important role in community development. The degree and direction of urban development is heavily dependent on the availability of this portion of the infrastructure.

service systems and are water supply engineers simply responding to demands placed on them by the population? Or, does the development of urban service infrastructure influence the growth and development of population? Are water supply engineers with their inherent tendency to encourage development of the water system also influencing the cultural, social, economic, demographic, and spatial development of the urban area they serve? Conventional wisdom holds that most water supply utilities merely serve the public, which demands increasing service. But, are utilities perhaps influencing this demand as well as serving it? No one study can answer these questions nor is such an attempt made here. But, by examining the development of the case study water supply infrastructure and its relationship to population growth, some additional insight may be derived.

Variables chosen for study were Population Density, Pipe Age, Pipe Volume, and Distance from the Central Business District (CBD). Data for the variables were arranged by census tracts beginning in 1940. This date was chosen because (1) utility data are most complete as of this date, and (2) the great surge of suburbanization occurred between 1940 and the present.[7,8]

Population density figures per tract were computed from census information between 1940 and 1970. The date the pipe was first installed subtracted from 1980 yielded the present age of the pipe. To relate age to population density a weighted average age was computed per census tract by multiplying the age of each pipe by its length; adding together the product to get a sum per tract: and then dividing by the total feet of pipe in each tract. Pipes 6 inches in diameter or greater which represent the major transmission of water as opposed to local distribution were used in this analysis. These pipes represent approximately 7.2% of the total miles of the pipe in the system.

Pipe volume, essentially pipe density, was calculated by dividing the total volume of a pipe in a census tract by the acreage of the tract. This provided a measure of volume per acre of pipe in a census tract comparable to population density. Distance from the CBD was calculated by measuring the distance between the geographic centers of each census tract and the CBD.

Development of quantitative measures among these variables is difficult but a combination of these variables in conjunction with graphic techniques can be used to develop insight into the relationships under study. Suburbanization surged from the mid 1950's to the present and the inner city experienced a severe decline in population density (Figure 2). As population grew on the periphery of the city, increases in pipe volume became necessary near the CBD to supply the outlying areas (Figure 3). A visual comparison of the two figures reveals the volume per acre near the CBD continued to rise while population density declined.

CASE STUDY UTILITIES

Two utilities were used as the source of data for this report. The larger utility serves a population of nearly 3/4 million and, until recently, derived all of its water from one source. Now both plants have a maximum capacity of neary 260 million gallons per day (950,000 m^3/day). On a yearly average approximately 150 million gallons of water are pumped per day (560,000 m^3/day). The distribution system is made up of 3,900 miles (6,275 km) of mains, 97.5% of which are cast iron, 2.1% are reinforced concrete pipe, and less then 1% are steel.

The smaller utility located near the larger utility serves a combination of rural and urban users and also draws water from two sources. Treatment in 1979 yielded 6.7 billion gallons of water (25.4 billon liters). Most of the 360 (579 km) miles of pipe are cast iron; the remainder are reinforced concrete or steel.

SYSTEM DEVELOPMENT AND POPULATION GROWTH

In this section, population growth will be examined in terms of population densities in various time periods versus distance from the city center. Water service network capacity will be examined in terms of pipe volume and density. Data from the larger of the two utilities has been used for this analysis.

The capital facilities that make up urban service networks such as water supply delivery systems, sewage collection networks etc., are often called the urban infrastructure. In this section, the relationship between the water supply network portion of the infrastructure and population growth and development will be studied for the metropolitan area served by the larger water utility. Basic units of analysis are census tracts.

Population density figures were computed from 1940 through 1970 census information and from 1970 Chamber of Commerce information. Because census tracts have been added and some boundaries have changed over the years, all volume and density calculations were made using the 1970 Chamber of Commerce areal data as a baseline. That is, those census tracts that changed size (gained or lost area) were standardized based on 1970 values so that population changes from decade to decade could be compared more easily.

INFRASTRUCTURE AND POPULATION DISTRIBUTION

What is the impact of urban services on population dispersion and growth? Does population growth dictate the development of urban

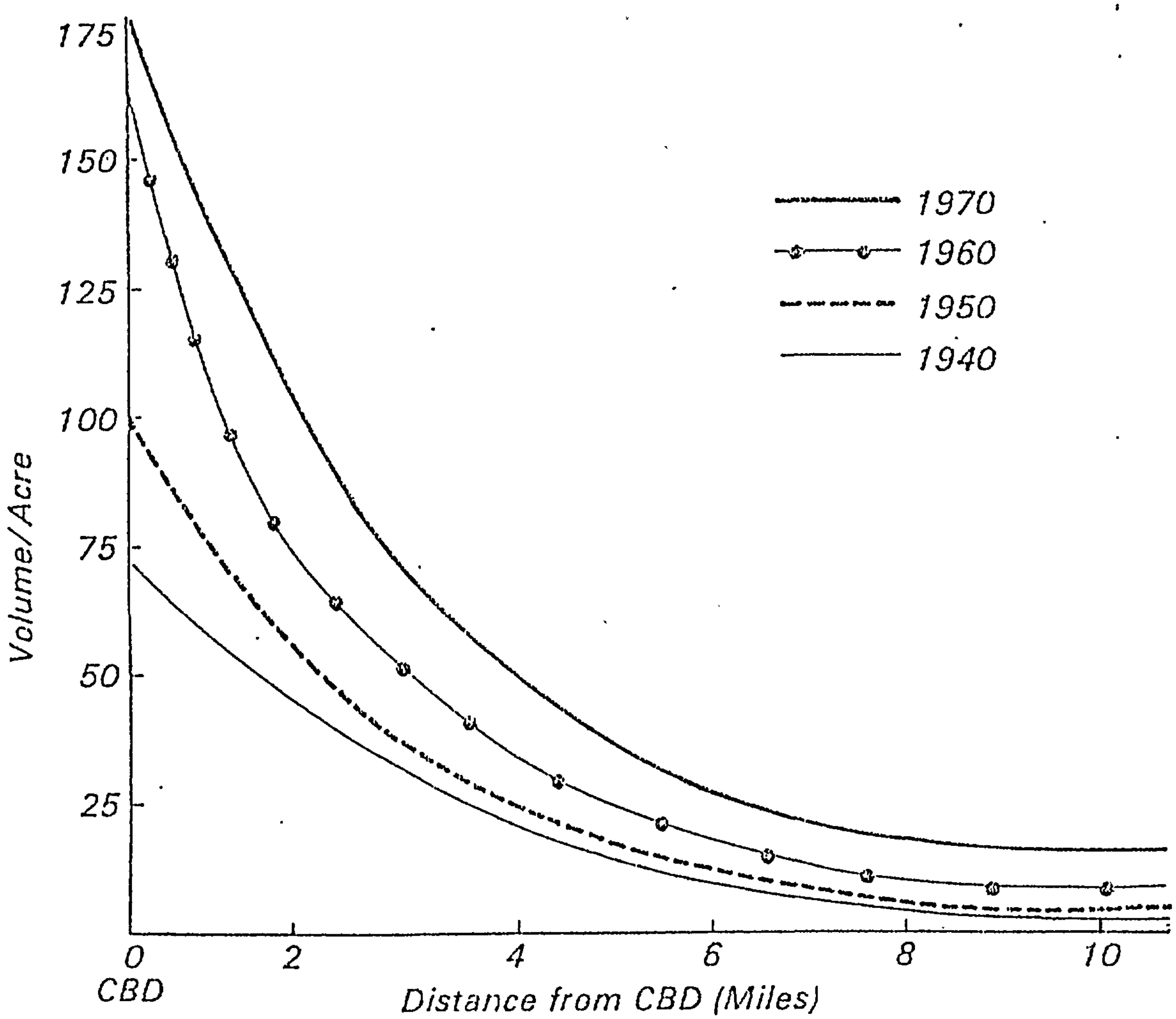

Figure 3. Volume/acre of pipe for a large utility (1940-1970).

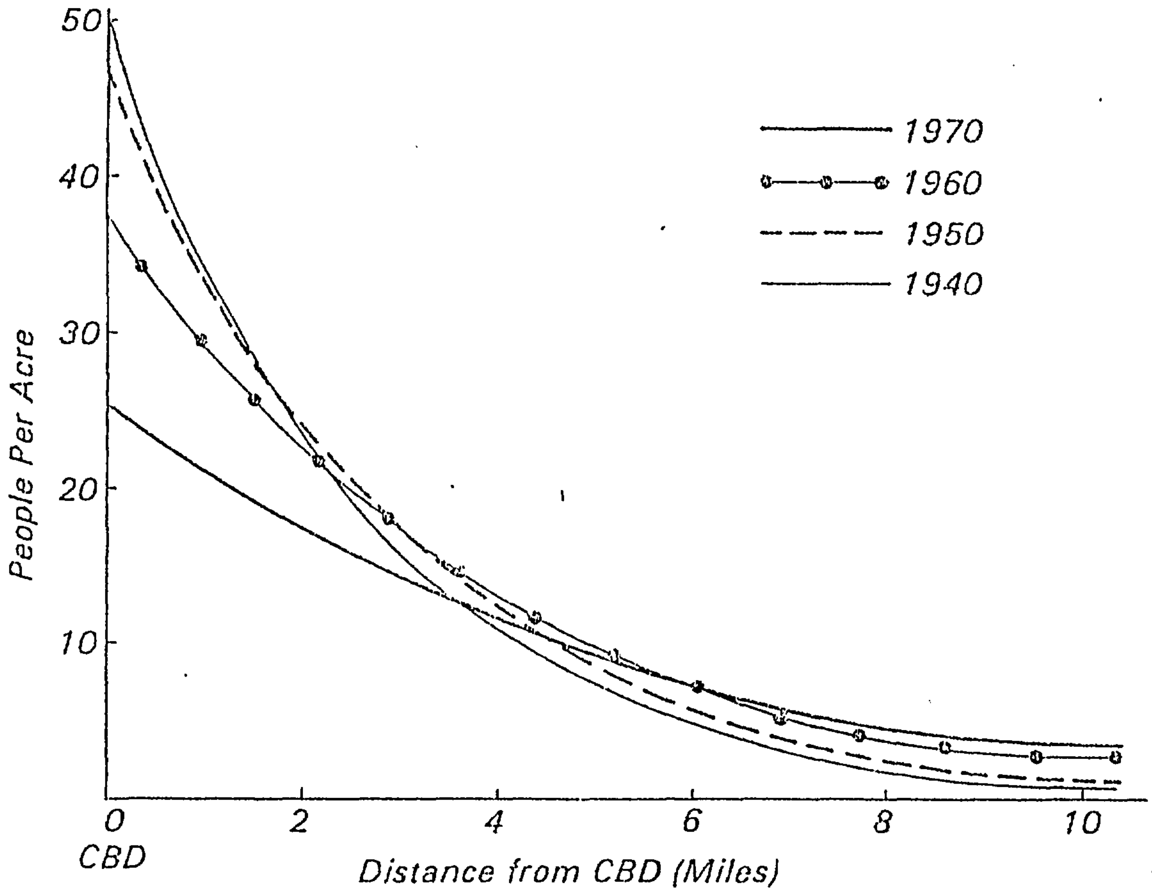

Figure 2. Population density for a large utility (1940-1970).

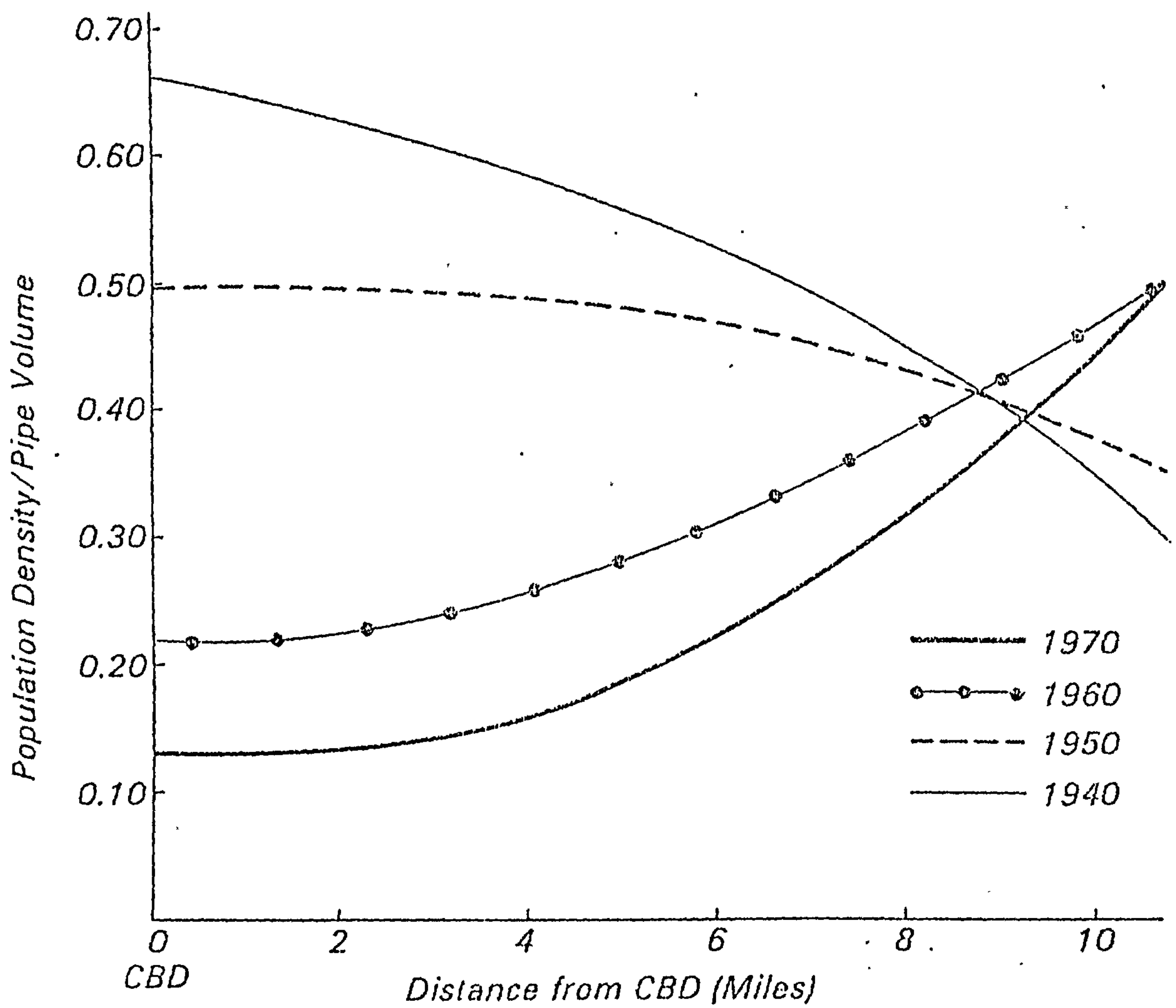

Figure 4. Ratio of pipe volume to population density.

POPULATION DENSITY AND PIPE VOLUME/ACRE

Two equations were developed in an attempt to relate the change in population density (PD) and pipe volume/acre (PVA) versus distance from the CBD:

$$PD = (33.5958)\,(e^{-0.005})^{AY}\,(e^{-0.223})^{CBD} \quad (R^2 = 0.48) \qquad (1)$$

$$PVA = (30.9323)\,(e^{0.027})^{AY}\,(e^{-0.204})^{CBD} \quad (R^2 = 0.52) \qquad (2)$$

where

PD = population density in people/acre;

PVA = pipe volume/acre in ft^3/acre;

AY = age of pipe in years;

CBD = distance from CBD in miles.

From equations (1) and (2), PD and PVA exhibit similar distance decay relationships for a constant AY. However, the relative values of the constants in the two equations show that for a constant distance, PD decreases in time but PVA increases. These relationships suggest that PVA tends to precede population.

Figure 4 is the ratio of PD to PVA for 1940, 1950, 1960 and 1970, versus miles from the CBD. In 1940 the ratio of PD to PVA decreased with distance. Once the pipes were in place, however, population could expand into the suburban areas. This relationship is confirmed by the flat slope and then the increasing slope of the lines for 1960 and 1970.

Census tract data support the idea that pipes precede population. In a number of outlying census tracts moderately large volumes of pipe were laid in the 1950's, but in 1970, population density for those census tracts remained very low.

The dilemma is comparable to that of the chicken and the egg. People need water, and therefore, will live where there is access to an existing water system. Pipes are laid, however, where planners anticipate people will live. The case study water works, used population estimates and projections to determine the quantity of supply required. Planning for system location in the utility service area initially followed transportation routes, and was extended to surrounding areas.

As urban growth continues and resources become increasingly limited, effective management of municipal water supply systems grows increasingly important. The relationship between the technology of

An analysis of water main breaks can provide insight into the reasons why breaks are occurring in a given area of the network or in a specific pipe. Insights from such an analysis can change pipeline design and construction policies and provide information as to whether or not a pipe should be repaired or replaced. In deciding whether to replace a pipe, the replacement cost and future costs associated with the new line should be compared with the cost of repairing the existing line and incurring possible future costs of repair and disruption of service.

During the course of this analysis the investigators found the definition of "break" to be difficult to establish. Examination of many years of data revealed that few actual "breaks" occurred, "break" in this context means a rupture of the line causing a cessation of service. A more subtle and insidious occurrence was continuous leakage from certain pipes causing maintenance crews to take remedial action. Therefore the analysis contained in this report is based on "maintenance events" or repairs but not on actual ruptures. A repair is defined as any event in which water was leaking and which a crew was sent to repair. These events do not include leaks from valves or clamps, but only joint or main line leaks. Valves and clamps were considered to be either internal or external fixtures but not part of the pipe itself.

Many factors were found to influence the number of maintenance events associated with a given pipe. The following sections contain an analysis of some of these factors and an economic evaluation of the optimal time for pipe replacement.

ANALYSIS OF MAINTENANCE EVENT DATA

Common sense and experience would indicate many variables might influence repair events. The basis for this study is a data set from the two case study water utilities consisting mostly of feeder and transmission mains. The data set includes the pipe lengths considered in the analysis, associated physical design and demographic data, and cost data. These mains have been categorized into 457 separate pipes. Separation into pipe links was based on a junction between pipes or a change in pipe diameter. No pipes laid before 1940 were used in the analysis. Break data for smaller pipes were virtually nonexistent. In Table 7 the pipes (by diameter) in the data base are compared with those in the distribution system of the two utilities.

water supply and its impact on socio-economic factors in urban areas should be examined. One view of this interaction is given in the following statement. "Water should be viewed as an economic good or service, not as a unique physical substance, nor as a fixed or limited resource. In the current water supply planning process we find the application of sophisticated engineering models, but only elementary and crude economic and demographic analysis."[7,8]

Results of the study show relationships between population, population distribution, and water supply. Water is not simply distributed in a haphazard fashion, and despite the tendency of the water supply profession to think in technical terms, significant socio-economic implications must be considered in their work. As society enters a period of growing concern over resource availability, allocation, and urban development, this important link should not be ignored. More research needs to be conducted in this important area.

ANALYSIS OF SYSTEM RELIABILITY

Facilities used for supplying water service, although predominantly of a more permanant character than those of other public utilities, are nevertheless subject to mortality and replacement. Because facility life is long, great difficulties arise in securing factual data relating to actual life and mortality experience. Even before a pipe reaches the point of ultimate replacement, as it ages, its carrying capacity can be severely reduced. Many cities are experiencing high maintenance rates indicating that their distribution systems are failing.[9,10,11]

As mentioned earlier, water main breaks disrupt service, reduce fire fighting capacity, may damage property, and pose a public health threat while incurring substantial repair and replacement costs. When a pipe breaks, the leak has to be located, the pipe excavated, and the leak fixed or a section replaced. A section of pipe experiencing a significant number of breaks or leaks, may be replaced entirely with a new pipe.

Shamir and Howard have categorized the reasons for breaks into the following categories:[12]

1. quality and age of the pipe itself, including connectors and other equipment;

2. type of environment in which the pipe is laid, e.g., the corrosiveness of the soil, frost and heaving, external loads;

3. quality of the workmanship used in laying the pipe; and

4. service conditions, such as pressure and water hammer.

because of overhead traffic, not because of differences in road surfaces. Traffic is only monitored at intersections, therefore data were not available for most of the intersections in the data base.

Weather information obtained from the U.S. Weather Bureau was complete. Data from appropriate regional planning commissions was the source of land use data for transportation, residential, commercial, and industrial activities for each census tract in the large utility's service area.

With the use of these data, a series of analyses was made incorporating: survival analysis, probability of maintenance event, maintenance event equations, economic analysis of replacement, and the impact of water quality on failure rate.

SURVIVAL ANALYSIS

A study was made of repairs to all pipes in the data base from the first through the tenth repair. Repair mortality curves (Figure 5) show that over a period of 40 years, 52.5% of the pipes studied had one or less maintenance events, 30% had two or less maintenance events, etc. These data indicate that a minority of pipes are responsible for a majority of the maintenance events. As will be seen in the following section, those pipes that had maintenance events, had them at an increasing frequency over time.

The life expectency of pipes was developed based on their ages and break history.[14] Five year old mains with no maintenance events can expect to have an additional 11.2 years without an event while 30-year old mains, 5.7 years, and 40-year old mains, 1-year (Figure 6).

TABLE 8. LIFE EXPECTANCY OF WATER MAINS

Age of main year	Time to first event, year
0	14.4
5	11.2
10	9.2
15	7.6
20	7.3
25	6.3
30	5.7
35	4.8
40	1.0

TABLE 7. COMPARISON BETWEEN DATA SET AND TOTAL FOR SYSTEMS

Diameter inches	(cm)	Length in data set (percent)	Length in actual system (percent)
3	(7.6)	0.00	0.21
4	(10.2)	0.00	1.62
6	(15.2)	1.70	59.85
8	(20.3)	6.30	22.34
10	(25.4)	0.99	2.17
12	(30.5)	10.40	5.60
16	(40.6)	18.15	2.64
20	(50.8)	4.57	0.66
24	(61.0)	23.00	1.95
30	(76.2)	5.30	0.45
35	(88.9)	0.12	0.02
36	(91.4)	17.30	1.56
40	(101.6)	0.00	0.01
42	(106.7)	4.00	0.31
48	(121.9)	4.28	0.30
54	(137.2)	0.75	0.06
60	(152.4)	0.90	0.07
84	(213.4)	1.50	0.11
96	(243.8)	0.90	0.77
		100%	100%

The following data were collected for each pipe section: diameter, material, age, pressure differential, absolute pressure, cleaning and lining (if performed), average amount of traffic traversing pipe in a 24-hour period, percent of length in low, moderate or highly corrosive soil, and number of freezes and thaws since installation.

In addition census tract data were collected to analyze the effect of surface development and land use on pipe breakage. These data are as follows: percent in transportation, percent in industry, percent in commerce, percent in residences, and population density.

Soil data were obtained from U.S. Soil Conservation Service maps, and pipe locations were plotted to determine surrounding soil type. The Soil Conservation Service provided the criteria for evaluating soil corrosivity, and determination was made as to whether or not the pipes lay in high, moderate, or low corrosive soil.

Most of the water works pipes are beneath city streets; only a few are installed beneath sidewalks. Traffic data were collected from both county and city data sources. Since most of the street pavement in the utility service area is uniform, stress upon the mains is primarily

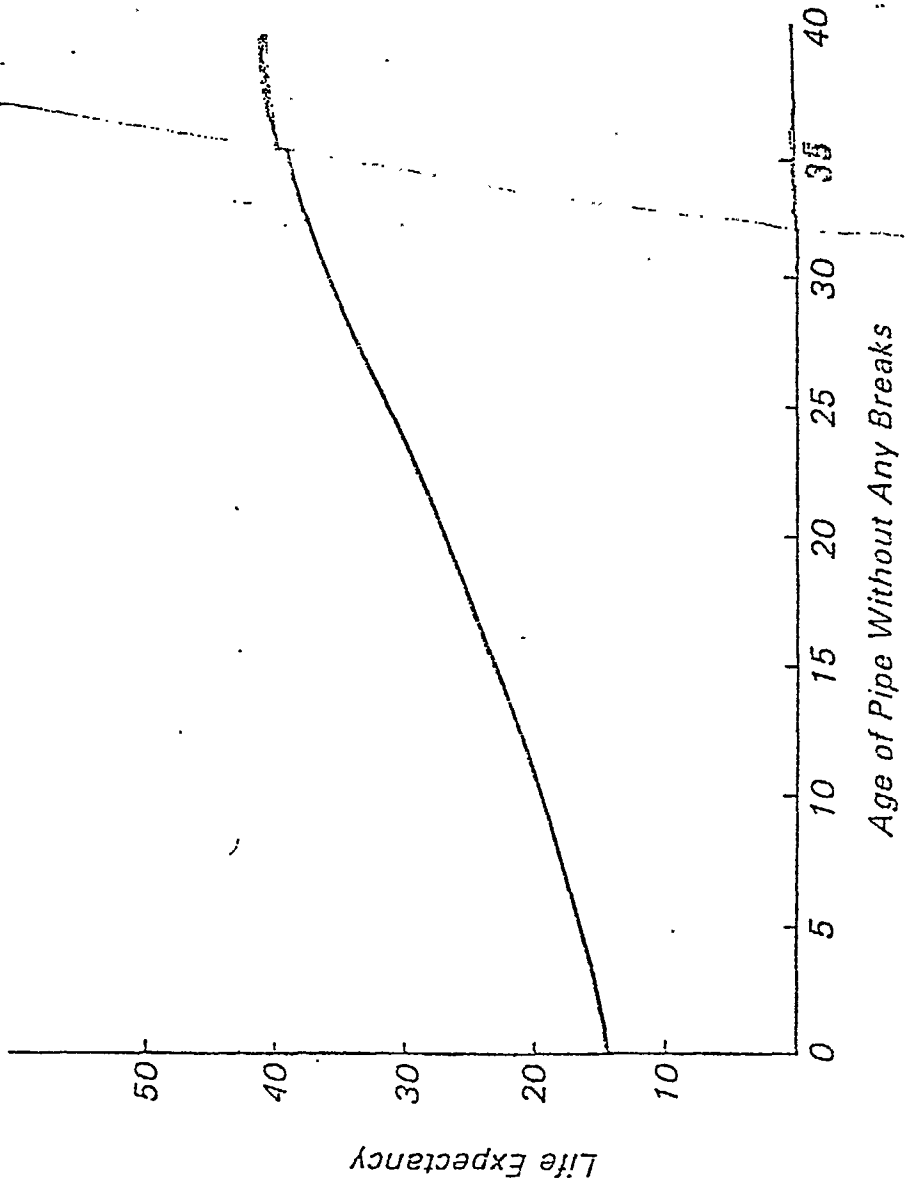

Figure 6. Life expectancy of pipes.

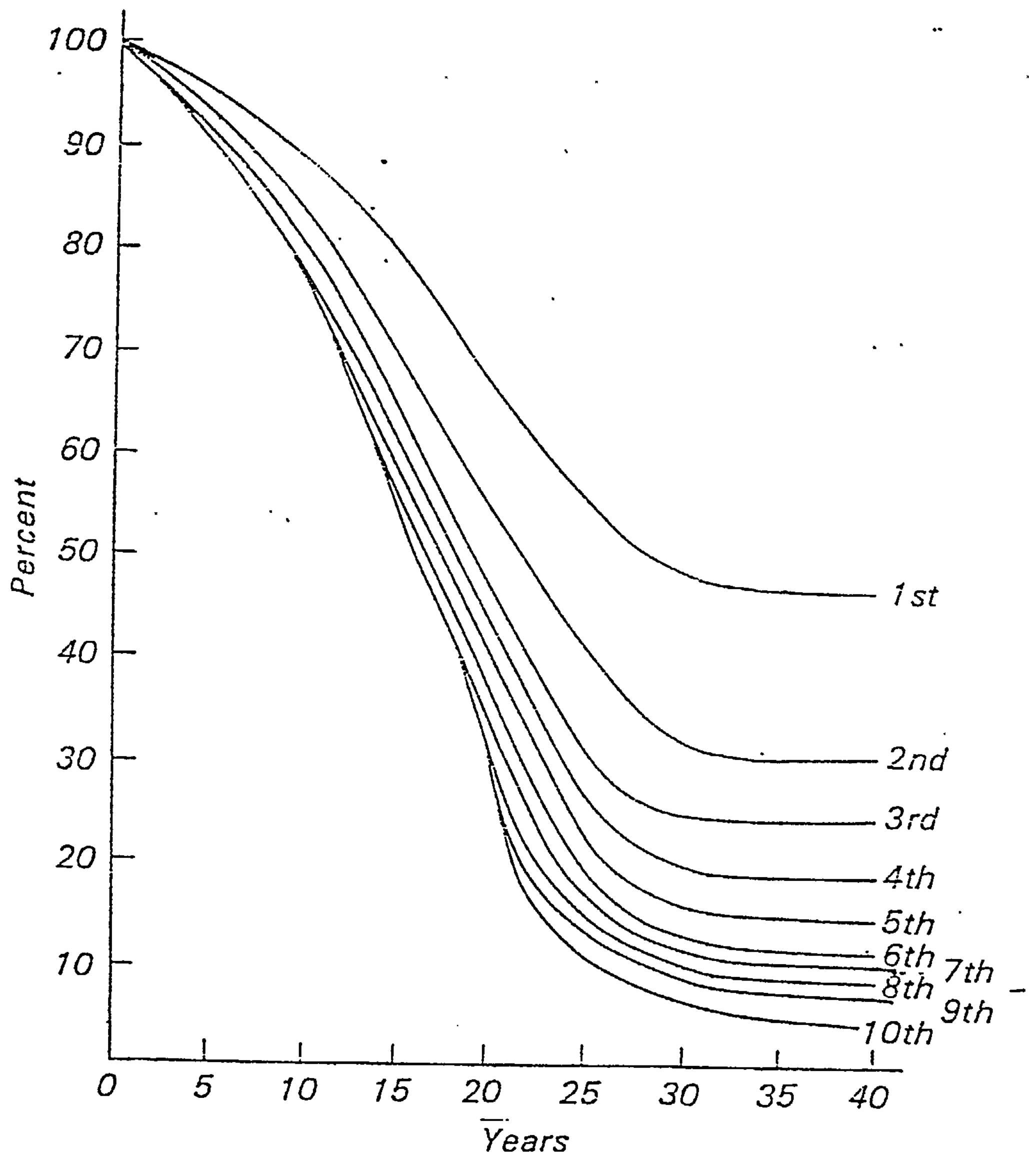

Figure 5. Percent having n or less repair events

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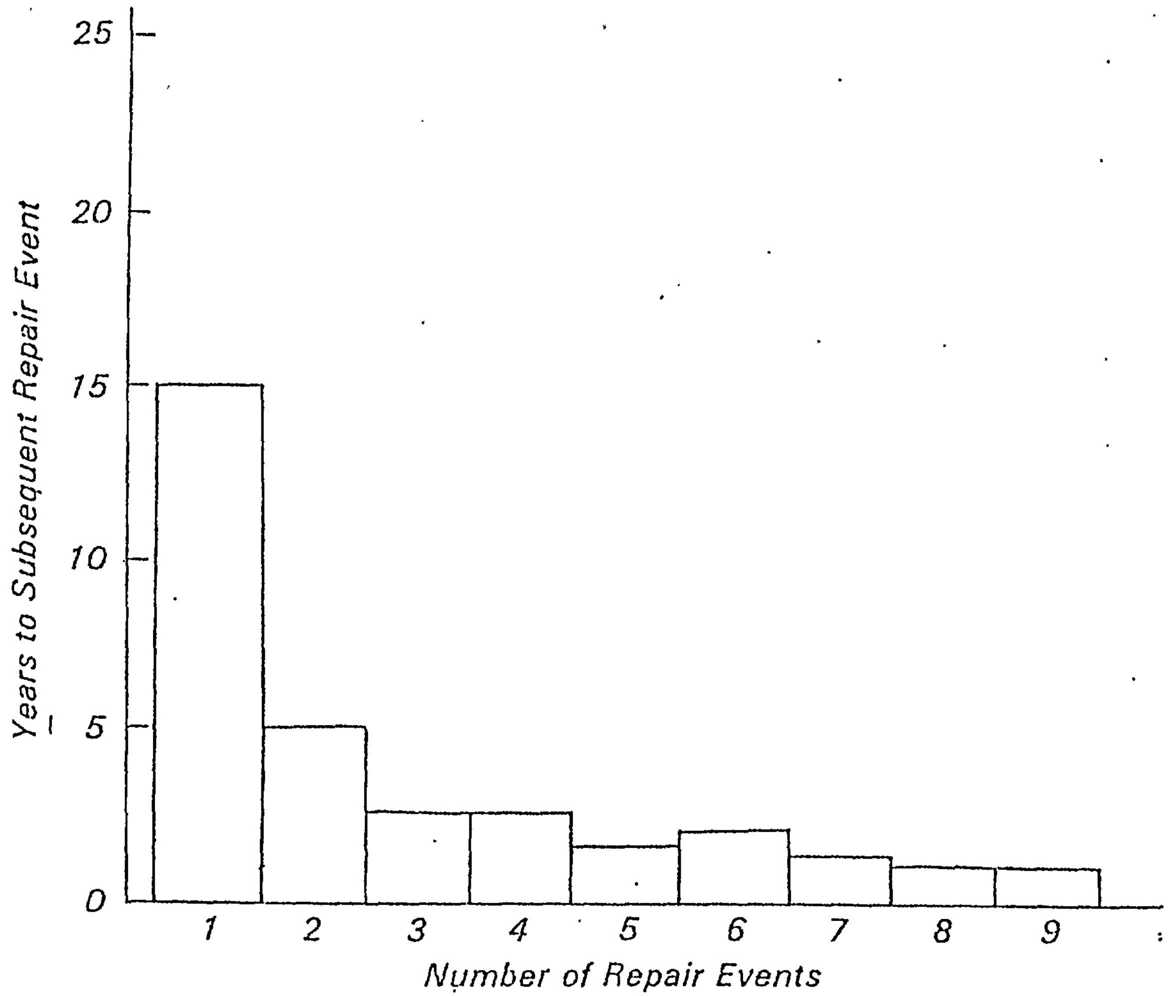

Figure 7. Average number of years to subsequent failure.

PROBABILITY OF FAILURE

Of the pipes studied, only a relatively small number experience maintenance events, even after long periods of time. For those that did experience such events, the time between one event and the next became increasingly short (Figure 7). To study this phenomenon, the interarrival time between repairs was formulated as an exponential function. Figure 8 shows the probability of a failure occurring at time t equal or less than time "T". The relative slopes of the curves indicate the time between a failure becomes increasingly short as the number of maintenance events increases. For example, given that a pipe has three events, the probability of having another event in a very short time is high. Table 9 summarizes the calculated values of λ for the failure equation:[15]

TABLE 9. CALCULATED VALUES OF LAMBDA

1	-.01
2	-.03
3	-.05
4	-.09
5	-.06
6	-.23
7	-.07
8	-.14
9	-.44

The values for λ shows a trend of increasing negativity (shorter period between breaks) until break four. At that point, because of the relatively small numbers of pipes in the data base having more than four breaks, lambda values begin to vary. To correct this inconsistency a regression equation relating λ to the number of failures was developed:

$$\lambda = 0.001 - 0.02B \qquad (R^2 = 0.53) \qquad (3)$$

where

B = repair number ($B \geq 1$).

Equation (3) can be used to estimate values for various number of breaks.

EVENT ESTIMATING EQUATIONS

Repair records were available after 1940 on 307 pipes considered in the original data set. Because the first maintenance event did not usually occur until 15 years after the pipe has been laid, the analysis could begin at 1930 instead of 1940 on the assumption that no breaks occurred in the first 10 years. Of the 307 pipes laid between 1930 and 1980, only 108 have been repaired. Figure 9 displays this break history between 1940 and 1980.

Examination of the data revealed that two underlying mechanisms seemed to be occurring with those pipes that experienced maintenance events. A lag period occurred between the time the pipe was laid and the first maintenance event. After the first event, the number of events seemed to increase exponentially. Therefore, two equations were developed, the first to estimate the time to the first event and the second, to estimate the number of events occurring after the first event. Equations were developed for both the large and small utility.

<u>First Event Equation - Small Utility</u>

The following equation predicts time from the initial installation to the first event (for those pipes experiencing events) for the small utility:

$$NY = 2.9 + 0.442D + 0.017P + 0.412I - 0.325RES \qquad (R^2 = 0.34) \qquad (4)$$

where

NY = number of years from installation to first repair;

D = diameter of pipe in inches;

P = absolute pressure within a pipe in PSI; (pounds per square inch)

I = percent of pipe overlain by industrial development in a census tract;

RES = percent of pipe overlain by residential development in a census tract.

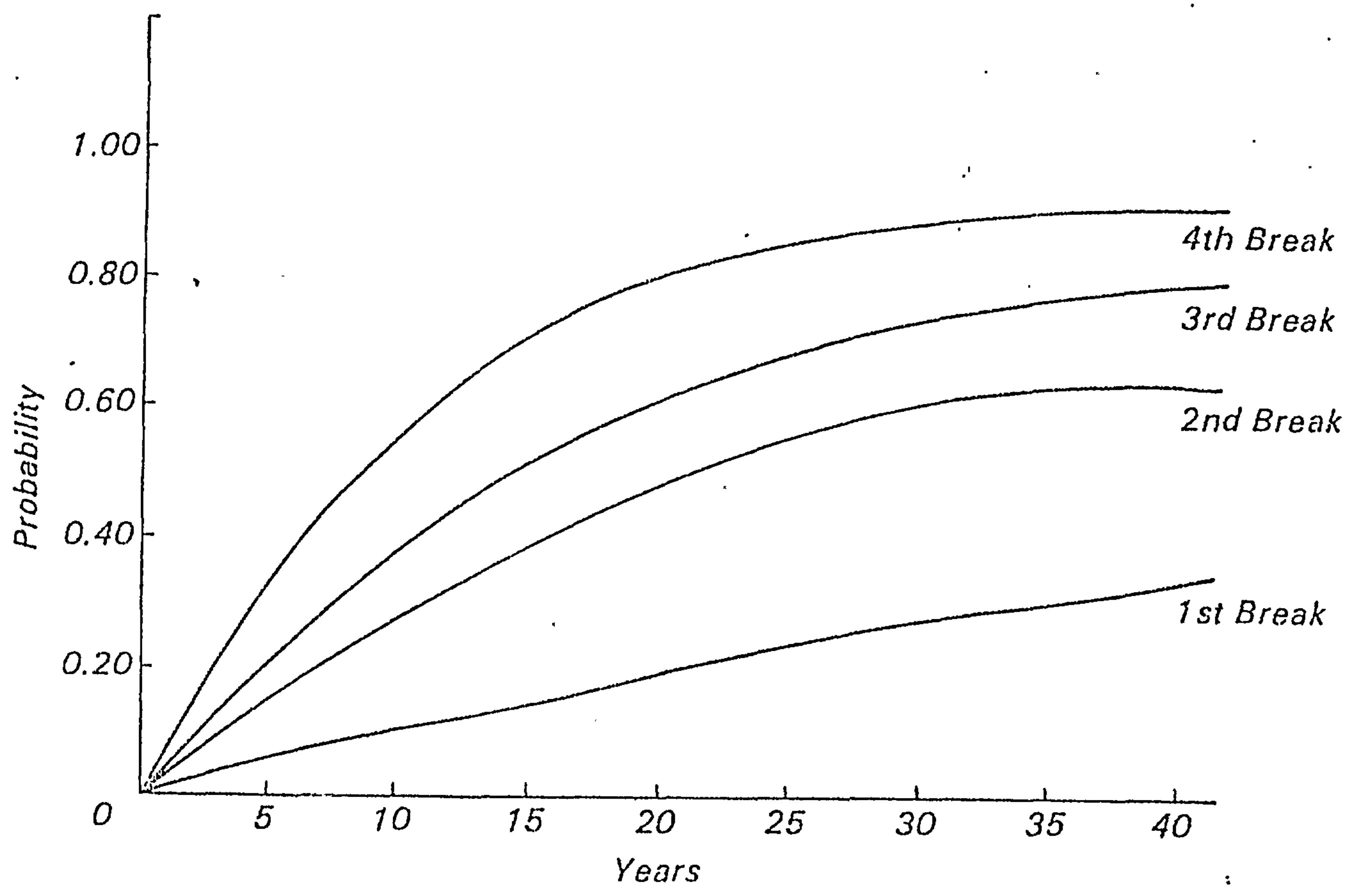

Figure 8. Probability of pipe failure.

The number of pipes that had useable data was 18, and the pipes analyzed were in the ground a relatively short time (13 years).

First Event Equation - Large Utility

The equation predicting the first event was as follows:

$$NY = 11.0 + 0.263D - 0.006P - 0.773I - 0.253RES - 0.00006LH + 15.69T \quad (R^2 = 0.34) \qquad (5)$$

where the variables are defined as in equation (4) and where

LH = Length of pipe in highly corrosive soil;

T = pipe type (1 = metallic; 0 = reinforced concrete).

In equation (5) soil corrosivity and pipe type entered the equation and the coefficents of P and I switched from positive to negative. The number of pipes considered in equation (5) was 68 and represented 40 years of data.

First Event Equation - Combined

Equation (6) represents the combined set of data:

$$NY = 4.13 + 0.338D - 0.022P - 0.2651 - 0.0983RES - 0.0003LH + 13.28T \quad (R^2 = 0.23) \qquad (6)$$

The coefficents in equation (6) as compared to equation (5) were relatively stable. The following Table contains the partial correlations for each variable considered in equation (6).

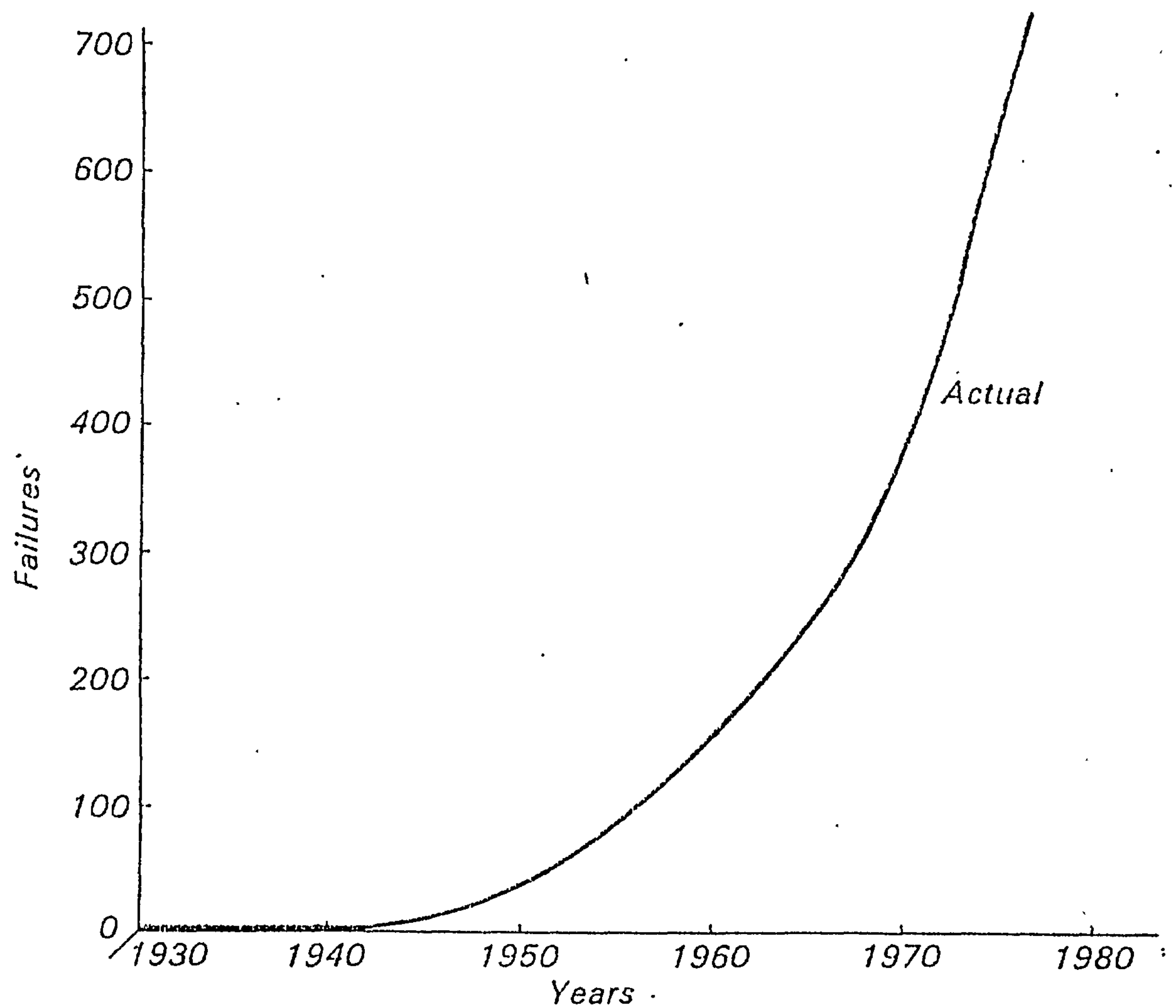

Figure 9. Break history for data set.

Accumulated Event Equation - Large Utility

$$REP = (0.172)(e^{0.7198})^{T}(e^{0.0040})^{PRD}(e^{0.0862})^{A}(0.0189)^{DEV}$$

$$(SL)^{0.014}(SH)^{0.069}$$

$$(R^2 = 0.47) \qquad (8)$$

where the variables in equation (8) are the same as previously defined and where

T = type of pipe (1 = metallic, 0 = reinforced concrete).

Accumulated Event Equation Combined

$$REP = (.1721)(e^{0.7197})^{T}\ (e^{0.0044})^{PRD}\ (e^{0.0865})^{A}\ (e^{0.0121})^{DEV}$$

$$(SL)^{.014}\ (SH)^{.069}$$

$$(R^2 = .47) \qquad (9)$$

The correlations for the variables in Equation (9) are in Table 11.

TABLE 11. PARTIAL CORRELATIONS

Variable	Partial
Type of pipe	.27560
Pressure differential	.16666
Age from first repair	.48159
Percent developed	.25051
Surface Area in Low and Moderate	.08055
Surface Area in High	.37972

The predicted events can be compared with actual events as estimated by equation (9) (Figure 10). Equation (9) must be applied to each pipe individually to estimate the number of breaks over time. Each of the variables considered in the analysis is discussed in the following sections.

TABLE 10. PARTIAL CORRELATIONS

Variable	Partial
Diameter	.27599
Absolute pressure	-.02211
Industrial %	-.37168
Residential %	-.41525
Residential %	-.41525
Length in highly corrosive soil	-.01996
Pipe type	.42638

Accumulated Event Equation - Small Utility

The equation that predicts the cumulative number of maintenance events after the first event is as follows:

$$REP = (0.386)(e^{0.0139})^{PRD}(e^{0.0602})^{A}(e^{0.0208})^{DEV}(SL)^{-0.016}(SH)^{0.025}$$

$$(R^2 = 0.49) \qquad (7)$$

where

REP = number of repairs;

PRD = pressure differential in PSI;

A = age of pipe from first break;

DEV = percent of land, over pipe, which is developed;

SL = surface area of pipe in low corrosive soil;

SH = surface area of pipe in highly corrosive soil.

Type of Pipe

Type of pipe varies from cast iron to reinforced concrete. Most mains in the data set are cast iron (CI) simply because the system was built at the time cast iron was used. During the 1930's, several steel mains were laid, but they are not prevalent. In the 1950's reinforced concrete pipe (RCP) was used for mains 24 inches (61 cm) or larger. For statistical reasons, pipe type was treated as a dummy variable. The value "one" was assigned to mains of metallic character [steel, CI, DI (ductile iron)] and "0" (zero) for RCP.

The entry of pipe type into the final equation with a positive partial correlation suggests that mains of metallic character are more susceptible to maintenance events than concrete mains. These events may result from many factors including corrosion, which will be discussed later in the report. Current industry trends are toward concrete, plastic and cast irons wrapped in polyethylene sleeving.

Pressure Differential

Pressure differential measures the maximum difference in absolute pressures within a main in pounds per square inch (psi). If a pipe is subjected to widely differing pressures, then stress may occur at certain points. Pressure differentials cause transients which are more damaging than absolute pressures. The effect of pressure differential is aggravated by metal loss due to external and internal corrosion. That pressure differential was more significant (higher R) than the mean absolute pressure in a pipe suggests that pressure differential is a superior measure.

Age From First Repair

The time from first event is the most significant variable in predicting the total number of events for a pipe over its lifetime. A main with maintenance events early in its life would have a much higher number of events than a comparable main that experiences maintenance events in later years. This characteristic is illustrated by the exponential tendency of the break history in the data base (Figure 9).

Developed Land Percentage

The percent of developed land is actually a combination of the four land use percentages (residential, commercial, industrial, and transportation) found in each census tract. These percentages were calculated in order to combat the inadequacy of the traffic data. Inclusion of the developed land percentages in the equation indicates overhead activity such as live load and drainage influenced the number of maintenance events for a pipe.

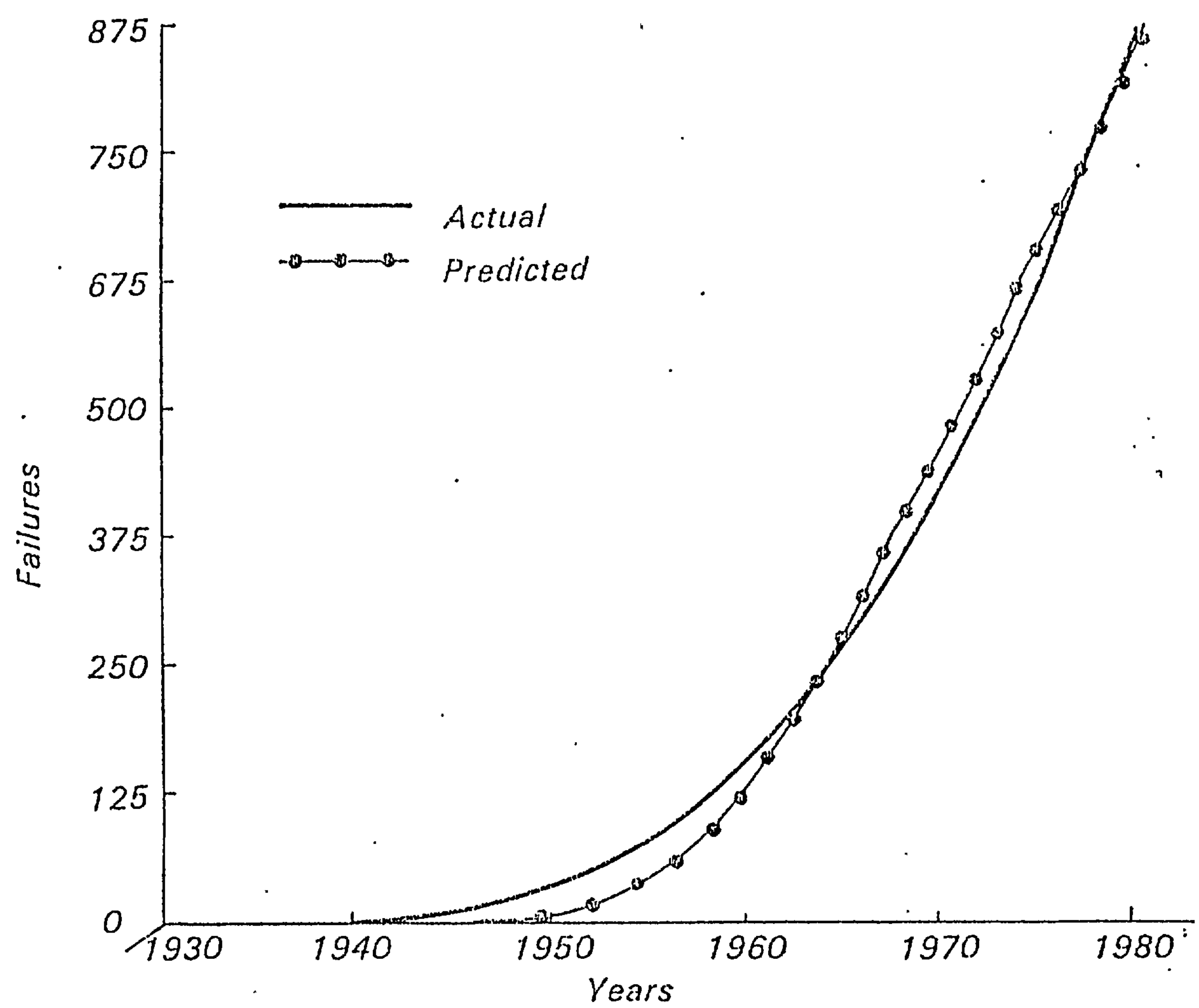

Figure 10. Predicted vs. actual breaks for combined data set.

cleaning and lining is necessitated by excessive tuberculation which is related to internal metal loss which in turn weakens pipe and leads to breaks.

Temperature

Temperature was a variable that seemed intuitively important but was found not to be significant. This lack of significance is because of problems inherent in the data. Typically, more events should be expected at lower temperatures, but in actuality this was not the case. Emergency breaks must be distinguished from nominal events (those which can be left until some later date), but according to a summary of pipe breakage by months in the data base since 1940 (Table 12), more events occurred in summer months. Temperature subsequently failed to yield significant results in the statistical analysis. Table 12 shows events by month for the large utility data set.

TABLE 12. SUMMARY OF REPAIRS BY MONTHS (LARGE UTILITY)

Month	Actual Number	Percentage	Month	Number	Percentage
January	53	5	July	136	12
February	83	7	August	116	10
March	68	6	September	83	7
April	66	6	October	111	9
May	108	9	November	109	9
June	134	11	December	104	9

Table 13 shows an obvious effect of temperature for the years of extremely severe weather in 1976 and 1977.

The number of events increased dramatically for 1976 and 1977 and then returned to a normal pattern in 1978. The sharp decrease in temperature for these years may not have increased the total number of events but rather caused them to occur earlier.

Surface Area Effects

Surface area also combines several pieces of data. Size and length of pipe were combined to yield surface area (the area actually in contact with the soil). Surface area in low and moderately corrosive soil were combined into one category. Surface area was then multiplied by the percentage of its length in low, moderately and highly corrosive soil.

Although including surface areas for both corrosive categories in Equation (9) may appear contradictory, one must remember that the greater the surface area, regardless of soil type, the more events that should occur. From the table of partial correlations (Table 11), one can see that soil corrosivity does influence maintenance events. Surface area in highly corrosive soil has the larger partial correlation between the soil variables.

Cleaning and Lining

A variable not included in the final equation (based on cases of repair only, N = 108) but one that showed significance in regressions performed with all pipes (N = 308), regardless of repair or not was cleaning and lining. Conventional wisdom states that cleaning and lining benefits the utility in terms of cost savings for it generally costs about half the expense of pipe replacement.

In this analysis, cleaned and lined pipes experienced more events, perhaps because the cleaning and lining procedures jar the pipe from its settled position. Over time this could represent increased maintenance costs.

The equation below relates cleaning and lining to maintenance events:

$$REP = 2.43 + 3.31CL \qquad (R^2 = 0.02) \qquad (10)$$

where

N = number of maintenance events;

CL = cleaning and lining variable (1 = cleaned and lined; 0 = not cleaned and lined).

Although the R^2 is very low, the relationship is still significant at the 0.025 level. In this sample, cleaning and lining may only account for 2% of the variation in maintenance events, but in large systems this variable could be a significant factor in maintenance costs. Cleaning and lining probably correlates with breaks because

If the present year is denoted by t_p, and the (noninflationary) discount rate is R, then the present value of this maintenance cost is simply:

$$\frac{C_m(t)}{(1+R)^{t-t_p}} \tag{13}$$

Denote t_r as the year in which the pipe will be replaced. The present value of maintenance cost from the present year t_p to the year t_r is:

$$P_m(t_r) = \sum_{t=t_p}^{t_r} \frac{C_m(t)}{(1+R)^{t-t_p}} \tag{14}$$

substituting equation (12) into equation (14) yields:

$$= \sum_{t=t_p}^{t_r} \frac{C_b K e^{GR(t-t_o)}}{(1+R)^{t-t_p}} \tag{15}$$

If the new pipe will not have any new events, then P_m (t_r) represents all future maintenance costs. Other cases will be discussed later.

The cost of replacing a pipe, expressed in the same constant dollars as C_b, is C_r. The present value in year t_r of replacing a pipe in year t_p is therefore:

$$P_r(t_r) = \frac{C_r}{(1+R)^{t_r-t_p}} \tag{16}$$

TABLE 13. EFFECT OF TEMPERATURE FROM 1974 to 1978

Year	Number of Breaks
1974	749
1975	980
1976	1,195
1977	1,113
1978	723

TIMING OF REPLACEMENT - ECONOMIC ANALYSIS

According to previously developed analyses the number of maintenance events in a given section of a pipe can be described by the following equation:[12]

$$N(t) = Ke^{GR(t-t_o)} \quad (t > t_o) \qquad (11)$$

$$N(t) = 0 \quad (t < t_o)$$

where

$N(t)$ = number of maintenance events in a given section of pipe;

K = constant resulting from the parameter values in equation (9);

t = number in years from installation;

t_o = number of years from installation to the first maintenance event;

GR = growth rate coefficient (dimension is 1/year).

As the number of events per year increases, so does the cost of responding to them. If the cost of repairing C_b, expressed in constant dollars, is assumed to be constant over-time, then cost of repair in a given length of pipe in the future year t is:

$$C_m(t) = C_b N(t) \qquad (12)$$

$$= C_b K e^{GR(t-t_o)}$$

TABLE 14. TYPICAL VALUES FOR EQUATIONS (6) AND (9)

Variable	Value	
D	20.97 in	(56.26 cm)
P	96.72 psi	(96.72 kN/m^2)
I	3.35%	
RES	34.43%	
LH	2598 ft	(791.87 m)
T	1 (metallic)	
PRD	33.47 psi	(230.78 kN/m^2)
A	10.3 years	
DEV	56.28%	
SL	55.85 ft^3	(1.582 m^3)
SH	76.54 ft^3	(2.164 m^3)
C_r	$87,500/1000 ft	($54,400/1000 km)
L	1680 ft	(3090 m)
C_b	$1430	
GR	0.086	
K	1.0445	
R	7.0%	
t_o	17 years	

The value for NY in equation (6) is t_o in equation (11). The constant in the fourth term of equation (9) is GR and the rest of the terms are calculated for K in equation (11). Equation (11) can be rewritten as:

$$REP = 1.1560\ e^{0.0865(t-17)} \qquad (20)$$

C_r and C_b are representative replacement and repair costs from the two utilities studied.

$P_m(t_r)$ is an increasing function of t_r, because for every additional year that passes before the pipe is replaced an additional term in equation (15) results. On the other hand, $P_r(t_r)$ decreases with t_r because C_r is assumed to be constant, whereas the demoninator increases with t_r.

The optimal timing for replacement is that for which the total cost

$$P_t(t_r) = P_m(t_r) + P_r(t_r)$$

$$= \sum_{t=t_p}^{t_r} \frac{C_m(t)}{(1+R)^{t-t_p}} + \frac{C_r}{(1+R)^{t_r-t_p}} \qquad (17)$$

is a minimum. Therefore determining the value of t_r, which minimizes equation (18), is essential, i.e.,

$$\underset{t_r}{\text{Min}} \; [P_t(t_r)] = \underset{t_r}{\text{Min}} \left[\sum_{t=t_p}^{t_r} \frac{C_b K e^{GR(t-t_o)}}{(1+R)^{t-t_p}} + \frac{C_r}{(1+R)^{t_r-t_p}} \right] \qquad (18)$$

Differentiating with respect to t_r, setting equation (18) to zero, and solving for t_r yields the optimal value:

$$t_r = t_o + \frac{1}{GR} \ln \left[\frac{\ln(1+R) C_r}{K C_b} \right] \qquad (19)$$

From equation (19) the value of t_r is 33.1 years using the values described below. Equation (6) can be used to estimate t_o and data from equation (9) can be used to estimate K and GR. Table 14 contains typical values from the data base used to estimate the parameters in equation (19).

$$\frac{\partial t_r}{\partial R} = 160.53 \qquad (27)$$

t_r will increase by 1 year for an increase of 0.6 percent or by 1.6 years for a 1 percent increase in R.

$$\frac{\partial t_r}{\partial K} = - 11.13 \qquad (28)$$

t_r will decrease by 1 year for an increase of 0.09 in K.

$$\frac{\partial t_r}{\partial C_b} = - 0.0081 \qquad (29)$$

t_r will decrease by 1 year for an increase of \$123 in C_b.

$$\frac{\partial t_r}{\partial C_r} = 0.0001 \qquad (30)$$

t_r will increase by 1 year for an increase of \$10,000 in C_r.

Effects of Maintenance Events in New Pipe

All of the above results were for the case in which the new pipe will experience no events. What happens when the new pipe is expected to have breaks in the same pattern as the old pipe?

Shamir and Howard have shown that the optimal replacement time for a new pipe is as follows:[12]

$$t^*_r = t_o + \frac{1}{GR} \ln \left| \frac{\ln(1+R)\ [(C_r+P^*_m)\ B(t^*_c)+C_r]}{KC_b} \right| \qquad (31)$$

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SENSITIVITY ANALYSIS

The sensitivity of t_r to variations in each of the parameters in equation (19) can be studied by differentiating t_r with respect to GR, K, C_b, C_r, and R. the resulting differentiation yields:

$$\frac{\partial t_r}{\partial GR} = \frac{-1}{GR^2} \ln \left[\frac{\ln(1+R) C_r}{KC_b} \right] \qquad (21)$$

$$\frac{\partial t_r}{\partial R} = \frac{1}{GR(1+R) \ln (1+R)} \qquad (22)$$

$$\frac{\partial t_r}{\partial K} = \frac{-1}{GRK} \qquad (23)$$

$$\frac{\partial t_r}{\partial C_b} = \frac{-1}{GRC_b} \qquad (24)$$

$$\frac{\partial t_r}{\partial C_r} = \frac{-1}{GRC_r} \qquad (25)$$

Using typical values from the previous analysis yields the following values.

$$\frac{\partial t_r}{\partial GR} = - 248.13 \qquad (26)$$

t_r will decrease by 1 year for an increase of 0.004 in GR, or by 2.48 years for an increase of 0.01 in GR.

$$V = (CM) \frac{(i\ (1+i)^y)}{((1+i)^y - 1)} \tag{35}$$

where

V = value;

CM = cost of the pipe replacement in 1978 dollars;

i = interest rate;

y = year.

and comparing it to the predicted cummulative dollars spent on repair. Data from the large utility for 1971 to 1978 were used to develop the average repair cost per break. During this period, repair costs have fluctuated from $1,170/break to $1,760/break, with $1,430 the overall mean. Therefore, for the purpose of this analysis a repair will be assumed to cost $1,430.

In this example, a 16 inch (40.6 cm), 1,680 foot (3090 m) section of a steel main laid in 1937 was replaced with a 12 inch (30.5 cm) ductile iron main in 1978 at a cost of $138,122. The above values can be found in Table 14. This section had experienced 32 breaks in 41 years with the first break occurring 9 (t_0=9 in this case) years after installation. With the use of equations (6) and (9) the predicted repair costs can be compared with the actual repair costs. With the use of equation (12), for this steel pipe the optimal time of replacement occurred around 1969 instead of the actual replacement date in 1978. Figure 11 shows the various repair and replacement cost curves. In time, utility requirements may change, and problem pipes may be replaced by entirely different materials to avoid future problems; this must be taken into account in a utility's replacement strategy. Throughout the analyses, steel mains had an unusually high number of repairs, but unfortunately, not enough steel mains exist in the data set to allow individual regression analysis for steel pipes alone. From these data, prediction of when pipes should be replaced is possible. Applying these kinds of analyses to a specific pipe with precise accuracy may, however, be difficult.

COST OF MAIN REPLACEMENT

The cost of main replacement is, in itself, a function of several independent variables. Regression analysis reveals the dollar cost per foot of water main to be highly dependent upon: diameter of pipe, type of pipe, the percentage of the tract in transportation, communications, and utilities, and distance from the CBD.

where:

$$t^*_c = \frac{1}{GR} \ln \left| \frac{\ln(1+R)C_r}{KC_b} \right| \qquad (32)$$

t_o = estimated lag between installation of new pipe and first break;

t^*_r = the optimal replacement time

$$P^*_m = \sum_{t=1}^{t^*_c} \frac{C_b K e^{GRt}}{(1+R)^t} \qquad (33)$$

$$B(t^*_c) = \frac{1}{(1+R)^{t^*} - 1} \qquad (34)$$

From equation (31) the optimal replacement time t^*_r is 36.2 years.

However, the discounted costs of a new pipe in the future will have little effect on the value of t^*_r.

EXAMPLE CALCULATION

From the previous analysis, water utilities will obviously be spending an increasing share of their budget on repair and maintenance. Tables 2 and 3 showed that the bulk of costs to a utility were for delivery and that the O&M costs for delivery were increasing. To illustrate some of the decisions that utility managers will be forced to make, a tradeoff analysis between repair and replacement cost is presented.

Given the predictive equations, the number of times a pipe might break can be estimated. Such an analysis can aid in making the decision between continued repair or replacement. Should a main encounter an increasing number of repairs, the main should be replaced before the dollars spent on repair exceeds the amortized value of the main in the ground. A cost trade-off can be calculated by taking the actual historic cost of laying a main, updating it to present value by use of the construction cost index, and amortizing the cost by the formula:

Diameter is a rather obvious variable because as it increases, so does material cost per foot. Pipe type, with its positive partial correlation, suggests that metal pipes are more expensive than cement pipes. The entrance of the transportation percentage variable into the equation shows that as the congestion (development) of an area in which a pipe is to be installed increases, so will cost per foot (labor and handling). This is further emphasized by the relationship between the distance from the CBD and the installation cost which shows that the cost per foot decreases as the distance from the CBD increases. The relationship is shown below:

$$C/F = (3.13)D^{1.83}(0.176)^{T}(TP)^{0.055}(CBD)^{-0.216} \quad (R^2 = 0.68) \quad (36)$$

where

C/F = $/foot;

D = diameter in inches;

T = pipe type (1 = metallic; 0 = cement);

TP = percent of land use over pipe in transportation, communication and utilities;

CBD = distance in miles from CBD.

Pipe repair and replacement is compounded by the fact that older pipes lie in the central city and break more often than newer pipes. They also cost more per foot to replace because they lie under the most highly developed areas in the city.

INFLUENCE OF WATER QUALITY

Water quality may also affect repair and replacement costs in water distribution systems, e.g., corrosive water may increase the number of breaks in water systems. Analyzing the effects of water quality within a single utility is difficult because water quality is generally uniform throughout the system.[16]

The corrosivity of drinking water is a parameter that has health and economic significance as well as aesthetic significance. Corrosion in a distribution system may add contaminants to finished water before it reaches the consumer. Some of these contaminants, such as lead and cadmium, at sufficiently high concentration levels in drinking water, may constitute a health hazard.

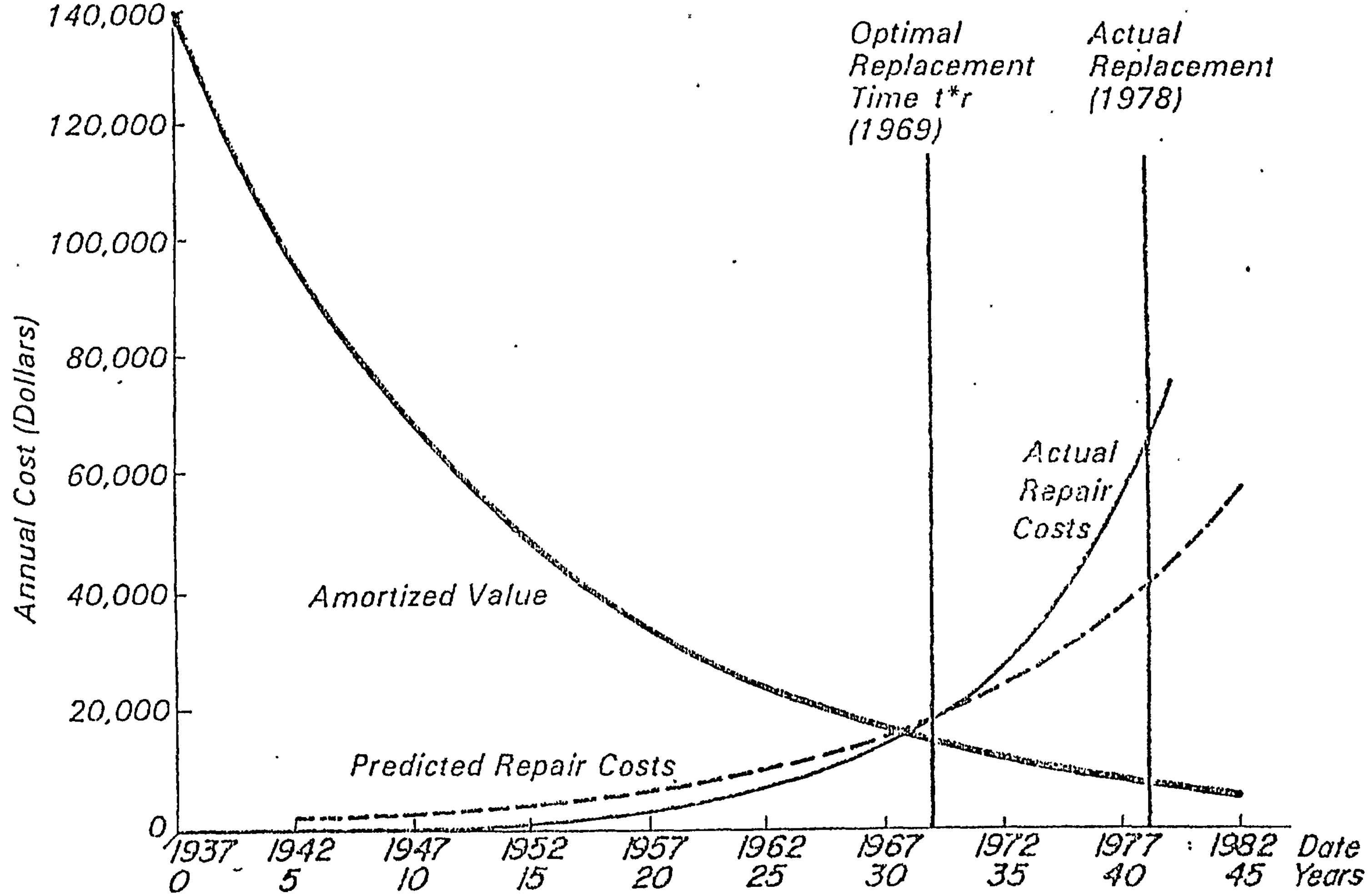

Figure 11. Repair vs. replacement costs.

Some of the signs of the coefficients in equation (38) appear counter-intuitive. Based on the above equation, however, utilities with small differences in elevation suffer significantly greater water loss. This loss could be because of a lack of pressure zones. Pressure zones are essential to ensure adequate water service in systems with hills; they allow pipes within these zones to be of similar internal pressure. Systems in generally flat terrains having only one pressure zone, with the pipe subjected to varying pressure, have increased breakage and a significantly greater percent of loss. Surface supplies also have a lower loss rate than do ground water supplies. This may be because most ground water supplies pump directly to the customer, and therefore, have higher pressure differentials than do systems that incorporate a large number of tanks and standpipes.

This cross-sectional study indicates that aggressive water is a factor, along with many others, in the cost of water supply. Although not conclusive, the results seem to justify more detailed case control studies of systems supplying either aggressive or nonaggressive water.

SUMMARY AND CONCLUSIONS

This report has dealt with problems associated with maintaining and replacing water supply distribution systems. Statistical models as well as graphic displays have been developed to examine the relationships between water supply infrastructure development and population distribution and growth. A technical economic analysis of the factors influencing the reliability of a water distribution system and associated costs for repair and replacement was made. The effects of water quality (corrosivity) on water loss and system cost was also examined.

The results of this study imply that a relationship between population distribution and water supply system development exists. Infrastructure development typically precedes even moderate population growth, and as society enters a time of growing concern over resource availability and quality and urban development, control of infrastructure development can be an important tool in urban morphology. This analysis implies that decisions by water supply planners may have significant socio-economic implications.

From the development of the equations for maintenance events several conclusions can be drawn:

1. metallic pipes take nearly 13 years more to experience maintenance problems than do reinforced concrete pipe. Once metallic pipes do experience maintenance problems they accummulate more maintenance events than do reinforced concrete pipes over a comparable period of time;

The annual loss from water corrosiveness has been estimated at about \$700 million.[17,18,19] In addition to the deterioration of the pipe used to convey water, water leakage from deteriorated distribution systems can be substantial. In some instances, as much as 25% of the water leaving a treatment plant is lost before reaching the consumer.

To analyze the effects of corrosion on water loss and cost of water supply, a sample of water utilities throughout the United States (60 in this case) was selected, and the hardness or softness of the water was determined. For the purpose of this analysis, if the raw water contained less that 60 mg/L of hardness as $CaCO_3$, it was considered soft. Utilities that altered their source water by treatment were placed in the appropriate category (hard or soft).

The analysis showed utilities with soft water had significantly higher total unit costs than those with less aggressive water. In fact, based on the following equation, unit costs should be 31% higher:

$$TUC = 460.96 + 205.73 W \qquad (R^2 = 0.07) \qquad (37)$$

where

TUC = unit cost in \$/MG

W = water quality (1 = aggressive; 0 = nonaggressive).

Obviously, the cost relationships associated with pipe failure and corrosion is much more complicated than the simple relationship shown in Equation (37). Although the R^2 is small the results are significant at the .05 level.

Another factor associated with corrosion is water loss. The following equation was developed based on the loss of revenue producing water as compared to the total water treated:

$$L = 0.0996 + 0.0804W + 0.001547FA - 0.0565S - 0.000029ELD$$

$$(R^2 = 0.34) \qquad (38)$$

where

L = loss percentage;

W = water quality (1 = aggressive; 0 = nonaggressive);

FA = age of first pipe;

S = source (0 = ground; 1 = surface);

ELD = elevation difference.

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2. large diameter pipes tend to have a longer period before the first maintenance event than do smaller diameter pipes;

3. large percentages of industrial development decrease the time until the first maintenance event;

4. amount of total land use development, increases repeat breaks.

The equations should not be used to predict maintenance events for individual pipes but can be used to indicate some of the variables that accelerate or retard maintenance events. Using these equations, scenarios were developed to describe the time of optimal repair and replacement. For the data used in this analysis the optimal repair period was slightly over 30 years.

Water quality may have an adverse impact on the maintenance event frequency for water delivery system pipes. Analysis revealed that utilities with aggressive water might expect up to 31% higher unit costs.

Throughout the various analyses, difficulties were encountered in the data collection. In many cases, the format for recording data was left up to various individuals throughout the years, and was, therefore, subject to much individual discretion. Most technical data obtained from agencies such as the National Weather Service or Soil Conservation Service were very good; however data from the utilities and planning agencies sometimes lacked consistency and completeness.

One conclusion to be drawn from this study is the need for water utility managers to institute careful record keeping procedures for tracking pipe repair and replacement costs. Significant savings can be achieved by replacing transmission and distribution pipes at the proper time. The issue of system deterioration will no doubt become much more significant in the future.

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA	2.	3. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE Determinants and Options For Water Distribution System Management: A Cost Evaluation		5. REPORT DATE January 1982
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Robert M. Clark, Cheryl L. Stafford, Micahel G. Laugle, and James A. Goodrich		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Drinking Water Research Division Municipal Environmental Research Laboratory 26 W. St. Clair St. Cincinnati, Ohio 45268		10. PROGRAM ELEMENT NO. PE BNC1A
		11. CONTRACT/GRANT NO. In - House
12. SPONSORING AGENCY NAME AND ADDRESS Municipal Environmental Research Laboratory - Cin.,OH Office of Research and Development U.S. Environmental Protection Agency Cincinnati, Ohio 45268		13. TYPE OF REPORT AND PERIOD COVERED Final - Nov. 1980 - Nov. 198
		14. SPONSORING AGENCY CODE EPA / 600/14
15. SUPPLEMENTARY NOTES Project Officer - Robert M. Clark (513) 684-7488		

16. ABSTRACT

This report deals with the problems associated with maintaining and replacing water supply distribution systems. Some of these problems are associated with publi health, economic and spatial development of the community, and costs of repair and replacement of system components. Statistical models are developed that demonstrates the relationship between population growth and development and growth of the water supply service network. A repair frequency analysis has been completed for distribution systems maintenance events (leaks and breaks). The economic implication of various replacement strategies and the effect of water quality (corrosivity) on water loss and system cost are examined. This analysis is based on the data acquire from one large (260 mgd; 950,000 m^3/sec) and one smaller (20 mgd; 75000 m^3/sec) water utility.

The capital facilities that make up urban service networks such as water suppl delivery systems, sewage collection networks etc., are often called the urban infrastructure. The water system infrastructure represents a major investment for a municipality. Because of the potential public health and safety implications of an adequate water distribution system, maintaining this system in good condition is an extremely important responsibility for water utility management. As this study show once a length of pipe begins to require maintenance, its maintenance rate increases exponentially. Maintenance costs soon exceed the costs of replacement. Therefore establishing a timely maintenance and replacement program is extremely important from an economic and public health viewpoint.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Economic Analysis; Economics, Land Use; Planning; Population; Regional Planning; Statistical Analysis; Water Supply; Water Distribution	Repair and Replacement; Pipe Failure; Regression Analysis.	13B 14A

18. DISTRIBUTION STATEMENT Release to Public	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES 54
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

EPA Form 2220-1 (9-73)

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