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Project Summary

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

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The report summarized here 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; 11.39 m^3/sec) and one smaller (20 MGD; 0.88 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 of a municipality. Because of the potential public health and safety implications of an inadequate 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.

This Project Summary was developed by EPA's Municipal Environmental Research Laboratory, Cincinnati, OH, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

Water supply service can be divided into a series of functions: support services, acquisition, treatment, and delivery. The treatment and delivery functions of a water utility represent large economic investments, but 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 (11.39 m^3/sec) capacity], which is examined in detail. The replacement value of the delivery system (not including treatment, acquisition and support services) is estimated at $917,814,700 based on 1978 dollar/foot rates. Maintenance of the delivery system in 1978 cost approximately $2,600,000 per year.

Not only does the water utility delivery system represent a large and important portion of the water utilities budget but it also plays a significant role in community public health and can become a determinant of the communities growth path. The degree and direction of urban development is heavily dependent on the availability of this portion of the infrastructure.

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.

Case Study Utilities

Two utilities were used as the source of data for this report. The larger utility serves a population of nearly three quarters of a million and, until recently, derived all of its water from one source. Now both plants have a maximum capacity of nearly 260 MGD (11.39 m^3/sec) and, on a yearly average, pump approximately 150 MGD (6.51m^3/sec). 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 billion liters). Most of the 360 miles (579.2 km) of pipe are cast iron; the remainder are reinforced concrete or steel.

System Development and Population Growth

For purposes of this analysis data was used from the larger of the two case study utilities. 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 chosed because (1) utility data are most complete as of this date, and (2) the great surge of suburbanization occurred between 1940 and the present.

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. As population grew on the periphery of the city, increases in pipe volume became necessary near the CBD to supply the outlying areas.

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. From the equations, PD and PVA exhibit similar distance decay relationships for a constant AY. Because of the relative values of the constants in the two equations, however, it can be seen that for a constant distance, PD decreases with time but PVA increases. These relationships suggest that PVA tends to precede population.

Results of the study show that there is a relationship 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, there are significant socio-economic implications to 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 permanent 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 is severely reduced. Many cities are experiencing high maintenance rates indicating that their distribution systems are failing.

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.

Pipes break because of the:

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.

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 it difficult to define "break." Examination of many years of data revealed that few actual "breaks" occurred; a "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 fix. These events do not include leaks from valves or clamps, but only joint or main line leaks. Valves and clamps are 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 that there are many variables that 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.

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: 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 a city data sources. Because most of the street pavement in the utility service area is uniform, stress on the mains is due primarily to overhead traffic not to differences in road surfaces.

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 were 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 1) show that over a period of 40 years, 52.5% of the pipes studied have 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, and them at an increasing frequeny over time.

It was also possible to develop the life expectancy of pipes based on their age. Five year old mains with no maintenance events can expect to have an additional 11.2 years without an event, whereas 30-year old mains have 5.7 years, 40-year old mains have 1-year remaining (Figure 2), etc.

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 (Figures 2 and 3). To study this phenomenon, the interarrival time between repairs was formulated as an exponential function. The relative slopes of the curves indicates the time between a failure becomes increasingly short as the number of maintenance events increases (Figure 4). For example, given that a pipe has three events, the probability of having another event in a very short time is high.

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.

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.

The predicted events can be compared with actual events as estimated by the two equations (Figure 5). Each of the variables considered in the analysis is discussed in detail in the final report.

Timing of Replacement — Economic Analysis

According to previous analysis, the number of maintenance events in a given section of a pipe can be developed from an equation. As the number of events per year increases, so does the cost of responding to them. Equations were developed to estimate the number of years from installation to the first maintenance event; a constant evolved from the number of repairs, the type of pipe, the pressure differential, the age of pipe from the first break, the percent of land over pipe in low and moderately corrosive soil, and the surface area of pipe in highly corrosive soil; and the growth rate coefficient.

Given the predictive equations, it is possible to project the number of times a pipe might break. Such an analysis can aid in making the decision between continued repair or replacement. If it can be shown that a main will encounter an increasing number of repairs, the main should be replaced before the dollars spent on repair exceed 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, amortizing the cost by a formula, and comparing it to the predicted cumulative dollars spent on repair. Data from the large utility for 1971 to 1978 was 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 was assumed to cost $1,430.

In this example, a 16-inch, 1,680-foot section of a steel main laid in 1937 was replaced with a 12-inch ductile iron main in 1978 at a cost of $138,122. This section had experienced 32 breaks in 41 years. With the use of equations, the predicted repair costs can be compared with the actual repair costs, and for this steel pipe, the optimal time of replacement occurred around 1969 instead of the actual replacement date in 1978. Figure 6 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, it is possible to predict generally when pipes should be replaced. Applying these kinds of analyses to a specific pipe with precise accuracy may, however, be difficult.

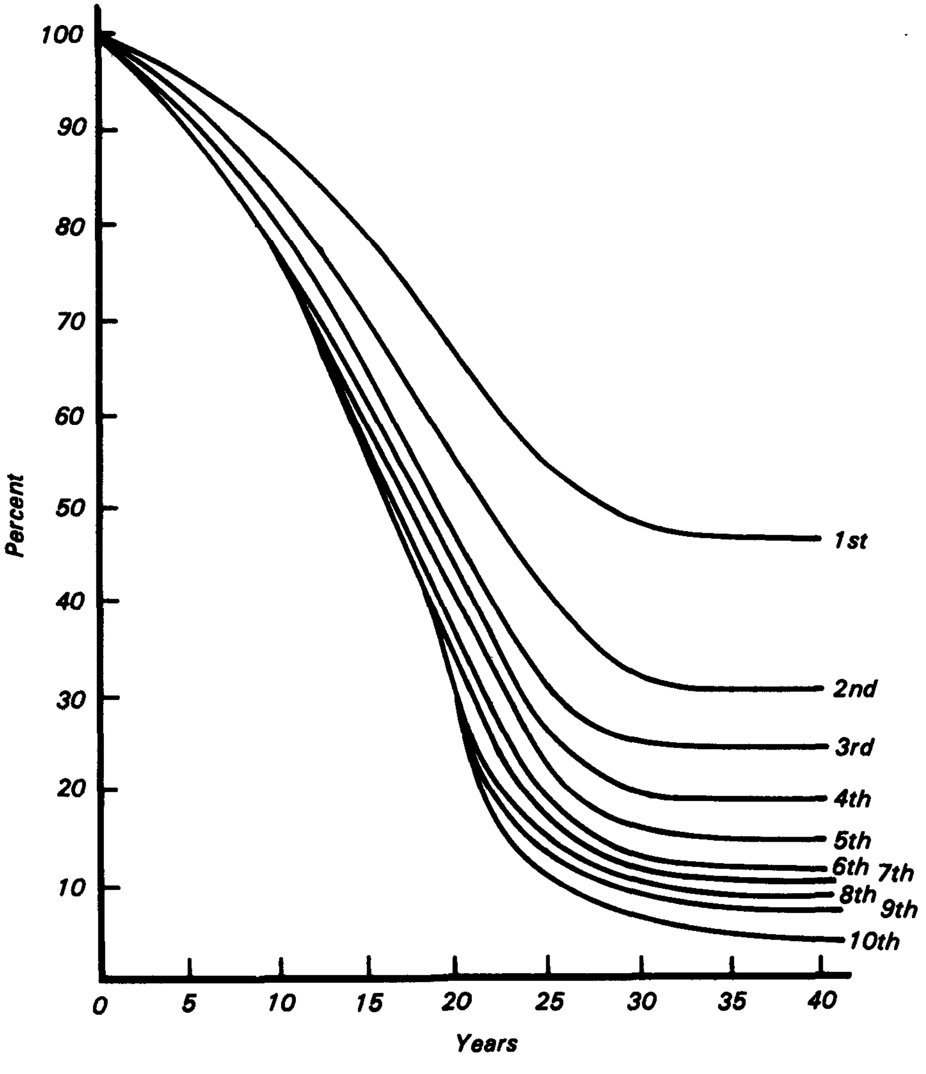

Figure 1. Percent having one or less repair events

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.

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.

The annual loss from water corrosiveness has been estimated at about $700 million. In addition to corrosion deteriorating 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, the hardness or softness of the water of 60 water utilities throughout the United States was determined. For the purpose of this analysis, if the raw water contained less than 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

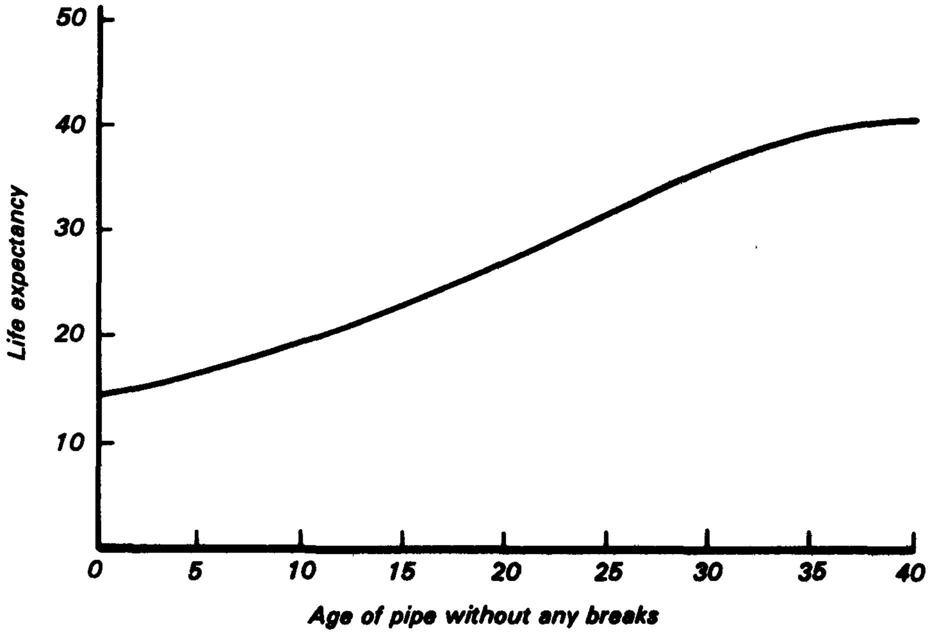

Figure 2. Life expectancy of pipes.

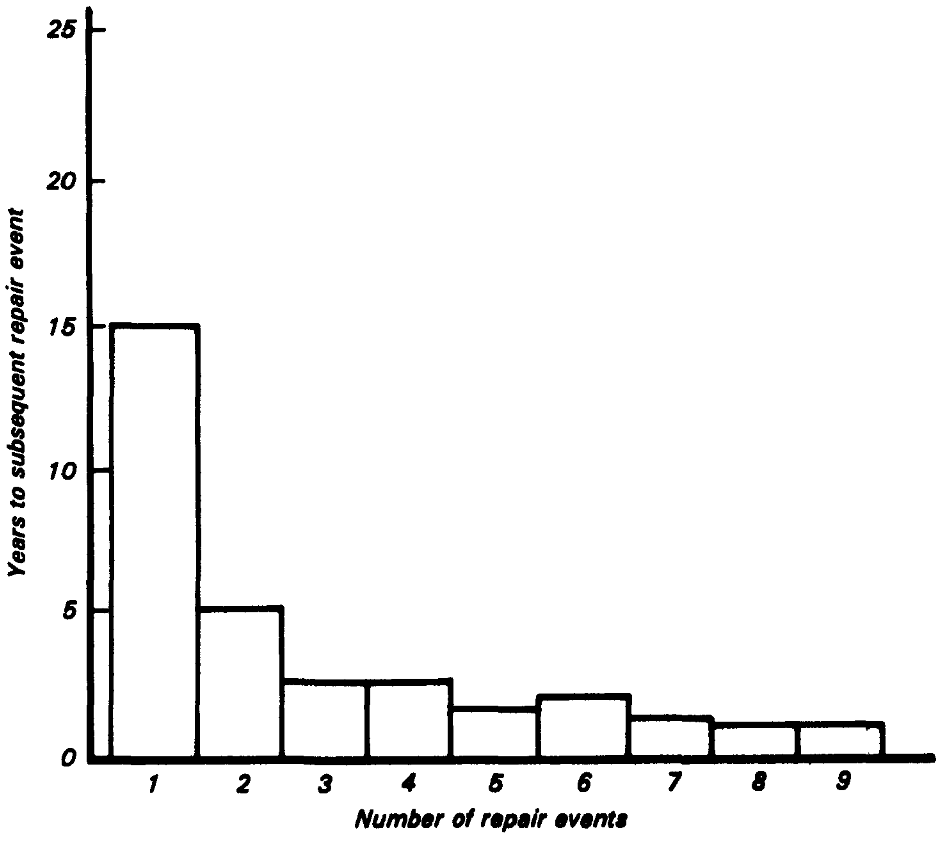

Figure 3. Average number of years to subsequent failure.

showed utilities with soft water had significantly higher (31%) total unit costs than those with less aggressive water.

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

Based on this equation, 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 have similar internal pressures. 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.

The cross-sectional analysis in this 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 indicate that there is a relationship between population distribution and water supply system development. 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

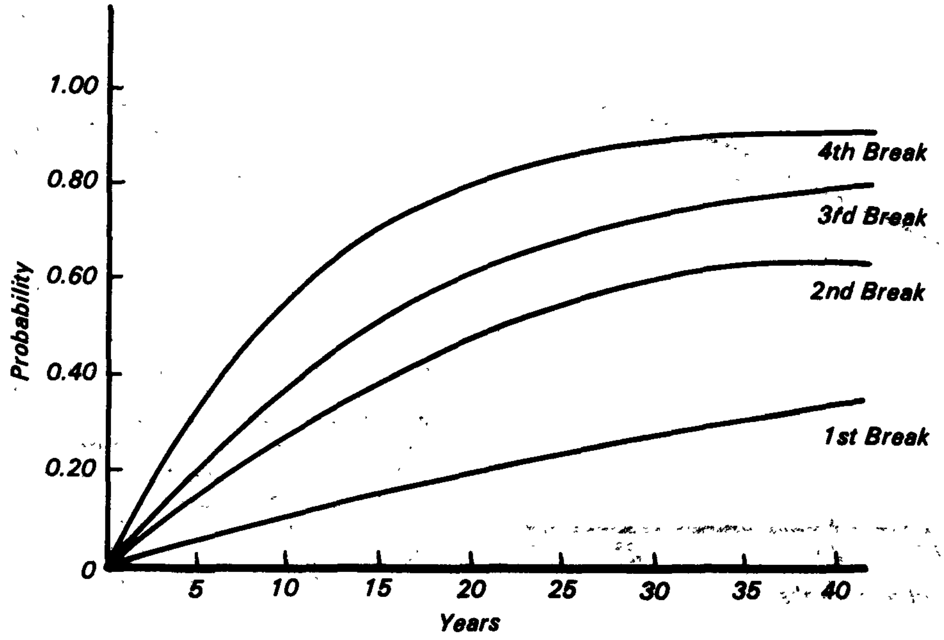

Figure 4. *Probability of pipe failure.*

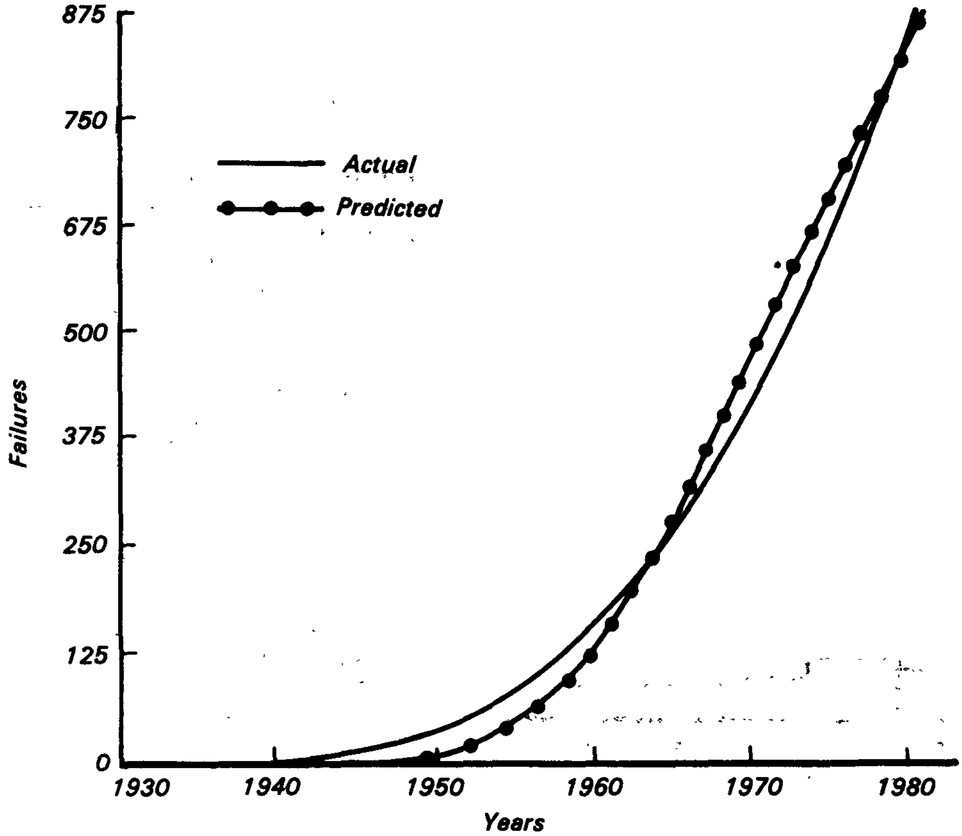

Figure 5. *Predicted vs. actual breaks for combined data set.*

important tool in urban morphology. This analysis implies that decisions b water supply planners may have significant socio-economic implications.

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

1. Metallic pipes take nearly 13 year more to experience maintenance problems than do reinforced concrete pipe. Metallic pipes accumulate more maintenance events than do reinforced concrete pipes over a period of time.
2. Large diameter pipes tend to have a longer period before the first maintenance event than do smalle diameter pipes.
3. Large percentages of industria development decrease the time until the first maintenance event.
4. The amount of developmen increases repeat breaks.

The equations should not be used fo predictive analysis but can be used to indicate some of the variables tha accelerate or retard maintenance events. Using these equations it was possible to suggest a scenario for the time of optimal repair and replacement. For the data used in this analysis, the optimal repair period was slightly ove 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 fo recording data was left up to various individuals throughout the years, and was, therefore, subject to much individual discretion. One conclusion to be drawn from this study is the need fo water utility managers to institute careful record keeping procedures for tracking pipe repair and replacement costs. Most technical data obtained from agencies such as the National Weathe Service or Soil Conservation Service were very good; however, data from the utilities and planning agencies sometimes lacked consistency and completeness. Because significant savings can be achieved by replacing transmission and distribution pipes at the prope time, the issue of a system's deterioration will no doubt become much more significant in the future.

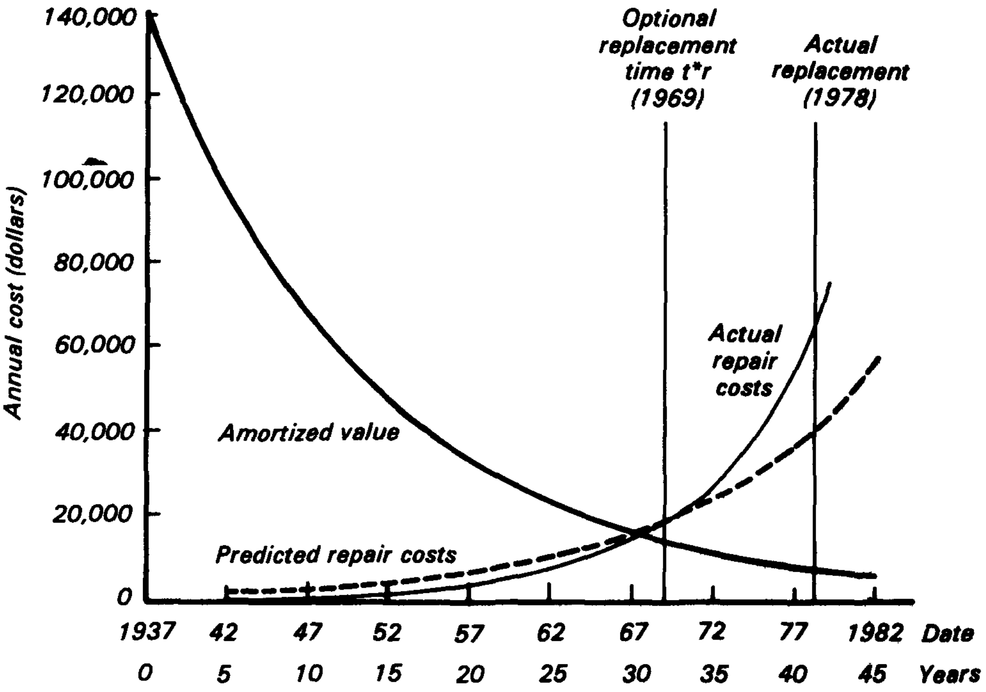

Figure 6. Repair vs. replacement costs.

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The complete report, entitled "Determinants and Options for Water Distribution System Management: A Cost Evaluation," (Order No. PB 82-227 745; Cost: $9.00, subject to change) will be available only from:

National Technical Information Service
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