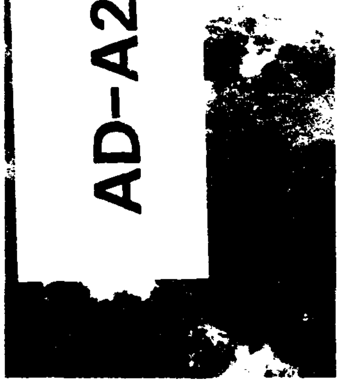
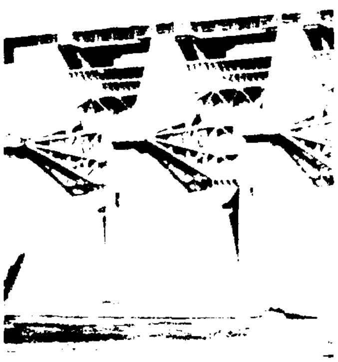
DTIC FILE COPY

(2)

US Army Corps of Engineers

AD-A219 212





TECHNICAL REPORT EL-87-9

NEW YORK WATER SUPPLY INFRASTRUCTURE STUDY
VOLUME V: ANALYSIS OF REPLACEMENT POLICY

by

James W. Male

University of Massachusetts
Amherst, Massachusetts 01003

Thomas M. Walski

Environmental Laboratory

DEPARTMENT OF THE ARMY
Waterways Experiment Station, Corps of Engineers
3909 Halls Ferry Road, Vicksburg, Mississippi 39180-6199

and

Adam H. Slutsky

Department of Civil Engineering
University of Massachusetts
Amherst, Massachusetts 01003

January 1990
Final Report

Prepared for US Army Engineer District, New York
26 Federal Plaza
New York, New York 10278-0090

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION
Unclassified

1b. RESTRICTIVE MARKINGS

2a. SECURITY CLASSIFICATION AUTHORITY

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE

3. DISTRIBUTION / AVAILABILITY OF REPORT
Approved for public release; distribution unlimited.

4. PERFORMING ORGANIZATION REPORT NUMBER(S)
Technical Report EL-87-9

5. MONITORING ORGANIZATION REPORT NUMBER(S)

6a. NAME OF PERFORMING ORGANIZATION
USAEWES
Environmental Laboratory

6b. OFFICE SYMBOL (If applicable)

7a. NAME OF MONITORING ORGANIZATION

6c. ADDRESS (City, State, and ZIP Code)
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

7b. ADDRESS (City, State, and ZIP Code)

8a. NAME OF FUNDING / SPONSORING ORGANIZATION
USAED, New York

8b. OFFICE SYMBOL (If applicable)

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER

8c. ADDRESS (City, State, and ZIP Code)
26 Federal Plaza
New York, NY 10278-0090

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)
New York Water Supply Infrastructure Study; Volume V; Analysis of Replacement Policy

12. PERSONAL AUTHOR(S)
Male, James W.; Walski, Thomas M.; Slutsky, Adam H.

13a. TYPE OF REPORT
Final report (in 5 vols)

13b. TIME COVERED
FROM ______ TO ______

14. DATE OF REPORT (Year, Month, Day)
January 1990

15. PAGE COUNT
114

16. SUPPLEMENTARY NOTATION
Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
Economics, Infrastructure, Pipe breaks, Pipelines, Rehabilitation, Water distribution, Water mains, Water supply

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This report is the last in a series that analyzes the water distribution system of New York City. It briefly summarizes important aspects of the previous reports, and presents an analysis of possible policies (strategies) for replacing segments of ~~the~~ water distribution system. Strategies were developed and tested, and compared with the Bureau of Water Supply's current strategy of replacing a main segment (equal to about 1/12 of a mile, on average) if it has had two or more breaks.

A mathematical simulation model was developed to conduct the analysis, which incorporates the cost of replacing water mains of different sizes and also the cost of repairing breaks that occur. Tradeoffs are involved: a very aggressive replacement strategy can result in excessive funds spent on capital-intensive projects, while a very passive replacement strategy might result in extremely high breakage in future years.

(Continued)

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT
☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION
Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL

22b. TELEPHONE (Include Area Code)

22c. OFFICE SYMBOL

DD Form 1473, JUN 86 Previous editions are obsolete. SECURITY CLASSIFICATION OF THIS PAGE

Unclassified

19. ABSTRACT (Continued).

With repeated applications of the simulation, the strategy that results in the lowest present costs (replacement plus repair) can be found.

The simulation allows analysis to be done 50 years into the future. It allows designation of the discount rate to be used when discounting to present value, and designation of a factor to account for indirect costs associated with a main break. Pipes were categorized into "bundles" based on their location (by borough), their size (6-, 8-, 12-, and 16- to 24-) in. diameters, and the period in which they were installed (before 1930, between 1930 and 1970, and after 1970). A Poisson distribution was used to convert average break rates into numbers of pipes having had 0, 1, 2, 3, and 4 or more breaks.

Overall, two types of strategies were examined. The first involved replacement of water mains once they had experienced a specific number of breaks. The second involved replacement of a fixed percentage of the distribution system each year.

Results of the simulation were sensitive to two factors: the inflation-adjusted discount rate and the magnitude of indirect costs associated with a main break. Analyses were carried out for ranges of both factors. As the inflation-adjusted discount rate increased, less aggressive strategies were selected as optimal. As the value of indirect costs was increased, more aggressive strategies were selected as optimal.

The most appropriate strategy for New York City is the current policy of replacing mains that have had two or more breaks. Although this strategy was not the least-cost policy under all circumstances (discount rate and indirect costs), it was the best in terms of being the closest to the optimal under a variety of input values. In addition, the two-or-more-break strategy resulted in a system with a relatively low break rate.

PREFACE

The study described in this report was requested by the New York State Department of Environmental Conservation, under Section 22 of Public Law 93-251. Responsibility for the project was assigned to the US Army Engineer Waterways Experiment Station (WES) under the direction of the Environmental Laboratory (EL). The work was managed and monitored by the US Army Engineer District, New York. Mr. David Schlessinger was the point of contact in the New York District.

This report was prepared by Dr. James W. Male, Department of Civil Engineering at the University of Massachusetts (working under the Intergovernmental Personnel Act with WES), Dr. Thomas M. Walski, formerly of the Water Resources Engineering Group (WREG) of EL, and Adam H. Slutsky, Graduate Research Assistant at the University of Massachusetts; under the direction of Drs. F. Douglas Shields, Jr., and Paul R. Schroeder, Acting Chiefs, WREG and Dr. John J. Ingram, Chief, WREG; Dr. Raymond L. Montgomery, Chief, Environmental Engineering Division; and Dr. John Harrison, Chief, EL. The report was edited by Ms. Janean Shirley of the WES Information Technology Laboratory.

The authors would like to thank the following people for their valuable contributions: Martin E. Engelhardt, Edward C. Scheader, Eugene Bard, Thomas D. O'Connell, Douglas S. Greeley, David Major, and Jerald Rosenberg, all of the New York City Department of Environmental Protection, Bureau of Water Supply; Howard Pike, New York State Department of Environmental Conservation; and Roy Wade, Water Supply and Waste Treatment Group, WES.

COL Larry B. Fulton, EN, was Commander and Director of WES. Technical Director was Dr. Robert W. Whalin.

This report should be cited as follows:

Male, James W., and Slutsky, Adam H. 1990. "New York Water Supply Infrastructure Study; Volume V: Analysis of Replacement Policy," Technical Report EL-87-9, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC)
UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
feet	0.3048	metres
inches	2.54	centimetres
miles (US statute)	1.609347	kilometres

NEW YORK WATER SUPPLY INFRASTRUCTURE STUDY

ANALYSIS OF REPLACEMENT POLICY

PART I: INTRODUCTION

Background

1. Water distribution systems are a perplexing component of the infrastructure of an urban area. Because water mains are beneath the ground there is no easy way to examine the condition of pipe segments making up the system. Existing approaches to the problem include leak detection to find undetected leaks, corrosion monitoring to track possible pipe deterioration, and flow rate and pressure testing to detect tuberculation and scaling resulting in decreased carrying capacity. None of these procedures, however, address the problem of pipe breakage. There is currently no economical and non-destructive means of testing a pipe segment for vulnerability to breakage.

2. A number of factors have been linked to excessive breakage rates: a) corrosion resulting in weakened pipes; b) prolonged leakage, resulting in erosion of supporting soil and increased electrical conductivity; c) insufficient load-bearing capacity; and d) direct contact with other structures. All of these factors depend on site-specific conditions, and must be addressed on the basis of one pipe segment at a time.

3. The only reliable way to plan for possible pipe breakage is to base predictions on past pipe break rates for specific categories of pipes. These categories can be based on location, materials, size, and the period in which the pipe was laid. Using this information, replacement strategies can be developed for categories of pipes. More detailed analyses can then be done on a site-specific basis to address localized concerns, such as carrying capacity, overhead load, etc.

4. Because of a concern over the water supply infrastructure in New York City, the Department of Environmental Conservation of the State of New York asked the US Army Engineer District (USAED), New York, to analyze the condition of the water supply infrastructure in New York City. Four reports have preceded this document, reporting on the condition of the five boroughs in New York City. Studies for the Manhattan and Brooklyn distribution systems

were conducted by Betz, Converse, and Murdock, Inc. (BCM) (USAED, New York 1980, 1984), while studies of the Bronx, Queens, and Staten Island were conducted by the US Army Engineer Waterways Experiment Station (WES) (Walski and Wade 1987 and Walski, Wade, and Sharp 1988). This report is based on the findings of the previous four documents and concludes the series of reports.

Purpose and Scope

5. The purpose of this report is three-fold: (a) to summarize the findings of the previous reports, (b) to present a procedure for analyzing pipe-replacement strategies, and (c) to draw conclusions from analyses using the procedure. The summary of the results will draw conclusions about characteristics that are similar for the five boroughs and point out important differences. The intent of the analysis of replacement strategies is to determine the most economically efficient level of replacement. A mathematical simulation model that calculates the present cost of different replacement policies was developed to assist in the comparison.

6. The premise for the determination of an economically efficient replacement strategy is that an aggressive pipe-replacement strategy will be expensive, but will result in a lower break rate, and will therefore lower costs associated with breaks in the long run. In a similar vein, a passive replacement strategy will not cost much initially, but will result in higher costs for pipe repair as poor main segments deteriorate and break at excessive rates. Figure 1 shows the hypothetical relationship of the present costs for the range of strategies between very aggressive and very passive. Presumably, somewhere between the two extremes, the present total cost (replacement plus repair) will be a minimum. If the choice of a strategy is based solely on economics, then this strategy should be selected.

7. The water supply infrastructure of New York City involves a number of components, including water supply sources, transmission mains, treatment facilities, pump stations, and the distribution system. This report is limited to the water distribution system. In addition, only one aspect of the distribution system will be considered; that of the pipes themselves. Pumps, hydrants, valves, backflow devices, and meters will not be considered.

8. The intent of this report is not to identify specific pipe segments that should be replaced (this was done in earlier reports), but rather to

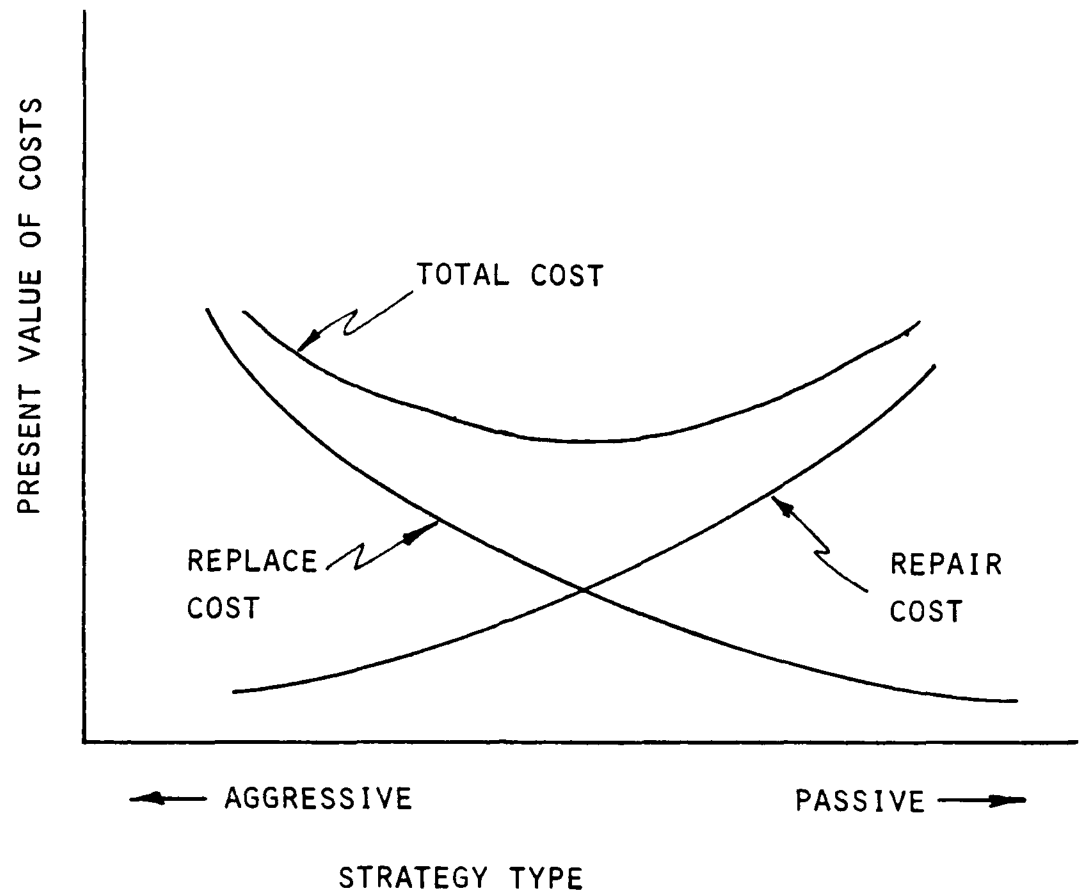


Figure 1. Relationship of present replacement, repair, and total costs

evaluate general strategies for main segment replacement. As such, bundles of pipes, made up of pipes with similar characteristics, will be addressed. For example, 20-in.* mains laid in Brooklyn before 1930 would make up a bundle. Once an appropriate strategy has been determined, it can be applied to specific categories. At that point, specific main segments can be addressed on a street-by-street basis. Clearly, the worst pipes within a category would be replaced first. In addition, an opportunistic approach to pipe replacement would clearly be advantageous; for example, questionable pipes could be replaced prior to (or in conjunction with) scheduled road resurfacing. Another factor that is not addressed in this report is the replacement of pipes because of poor carrying capacity. This issue is extremely important, and pipe replacement may be for both reasons (excessive breakage and poor

* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 4.

carrying capacity). However, the assumption throughout the analysis is that carrying capacity is sufficient, and main segments are replaced with pipes of the same diameter. The only exception to this rule is that all existing 6-in. mains are replaced with larger diameter pipes.

Organization of Report

9. Part II of this report is an overview and summary of the previous reports, with an emphasis on comparisons that were not possible as the reports were written. Part III describes the theory and mechanics of a simulation model that analyzes different replacement strategies, while Part IV presents information on the verification and calibration of the simulation, and the input data used in the analysis. Part V presents the results of the application of the simulation, and Part VI summarizes and concludes the report.

PART II: OVERVIEW AND SUMMARY OF PREVIOUS REPORTS

Overview

10. The intent of this part is to provide a synthesis of the documents prepared for each of the five boroughs. The important aspects of the previous reports are summarized and compared. The basis for the summary and comparison is information that was presented in the previous reports. Unfortunately this approach is limited by the fact that, although the general objectives of the reports were similar, they were conducted by a number of different individuals over an 8-year period. Hence not all of the reports used uniform data bases, nor were they consistent in their methodologies.

11. Studies of the boroughs of Manhattan and Brooklyn were conducted by BCM (USAED, New York 1980, 1984). The studies of the boroughs of Bronx, Queens, and Staten Island were conducted by WES (Walski and Wade 1987; Walski, Wade, and Sharp 1987). The early two reports contained considerable information on the causes and characteristics of breaks. Most of this information is universal and applies to all boroughs. The later two reports concentrated more on specific aspects of the three boroughs being studied, and made recommendations on specific segments of mains.

Data Sources

12. One of the most difficult aspects in analyzing the history of a water distribution system is the necessity of relying on data that were collected over a long period of time. The information on breaks, for example, must be collected and recorded when the break occurs. Over the years, collection procedures may change and record-keeping methods are often modified. In addition, the emphasis on maintaining accurate records may change over time, often depending on available resources.

13. Several sources of data were used in the reports on the five boroughs, and are listed below:

- a. The New York City Fixed Assets Accounting System Master File, prepared by Earnst and Winnie, and maintained by the city, contains a considerable amount of information about the city's infrastructure.

b. The US Census Bureau's Geographic Base File-Dual Independent Map Encoding (GBF-DIME) file, which contains information on streets that parallel water mains.

c. A "break file" containing information on each break that was prepared by BCM (1980) for the USAED, New York, for an earlier part of the New York Infrastructure Study.

d. Annual Reports of the Bureau of Water Supply.

e. Main-break reports, which are maintained by the Bureau, and contain information on breaks that have occurred in the city.

14. Later reports relied heavily on data collected and tabulated as part of earlier studies, particularly Manhattan (BCM 1980). Other information was also taken from the Bureau of Water Supply's records as a means of checking the accuracy of specific data. Information on the borough of Queens was incomplete because the city assumed responsibility for portions of the system from several other water utilities. As a result, records on a total of 319.3 miles of mains (approximately 8 percent of the system) were not available.

Main Inventory

15. The lengths of mains, arrayed by pentad (5-year period) laid and diameter, for each of the boroughs were obtained from the four previous reports. Table 1 lists the length of main by pentad laid for the five boroughs. A similar summary, delineated by diameter, is provided in Table 2. It should be noted that the total amounts shown in Tables 1 and 2 correspond to those in the Fixed Assets Accounting System Master File. These amounts are considerably less (roughly 10 percent, depending on the borough) than those found in the Bureau's records. One possible explanation for the difference is the inclusion of fire hydrant service connections in the Bureau's files.

16. It is clear from the tables that only a very small portion of the system has been installed in recent years. In addition, certain diameters are far more prevalent than others. This is due, in part, to the fact that the Bureau does not install certain diameter pipes; the most striking example is that of 10-in. mains. Also a majority (about 53 percent) of the pipe in place has a diameter of 8 in. or less and only a little more than 6 percent has a diameter greater than 24 in. The percentage of 6-in.-diam mains is steadily decreasing as the Bureau replaces these segments with larger pipes. In fact,

Table 1

Inventory of Mains by Pentad Installed (miles)

Pentad Laid	Bronx	Brooklyn	Manhattan	Queens	Staten Island	Total*
pre-1870		57.0	120.0			226.7
1870-74	0.2	28.1	17.1			95.1
75-79	1.7	9.7	33.4			94.5
80-84	1.8	14.1	20.7			86.3
85-89	5.1	22.2	41.2			118.2
90-94	7.2	71.0	18.7			146.6
95-99	14.8	75.0	42.2	51.9**		181.7
1900-04	31.9	96.7	36.4	0.3		207.6
05-09	61.3	183.0	55.6	4.7		346.9
10-14	61.8	173.4	23.4	422.7	58.6†	359.5
15-19	15.4	55.9	7.6	22.3	13.7	114.9
20-24	89.9	129.8	10.4	140.8	51.7	422.6
25-29	126.5	217.6	33.1	178.4	102.7	658.3
30-34	71.6	93.5	27.0	91.9	62.0	346.0
35-39	65.3	67.3	29.1	131.9	85.4	379.0
40-44	31.7	62.8	14.7	73.5	52.7	235.4
45-49	23.7	49.2	23.6	80.8	48.7	226.6
50-54	45.8	97.6	30.8	110.7	38.3	323.2
55-59	40.2	96.4	22.7	71.5	43.9	274.7
60-64	51.1	112.8	26.9	54.8	43.3	288.9
65-69	52.0	64.0	21.9	54.5	39.9	232.3
70-74	32.1	47.8	13.0	31.3	34.2	158.4
75-79	22.6	31.3	24.4	33.0	21.9	133.2
80-84	12.8	17.6	††	34.1	33.1	97.6
Total	866.5	1,874.6	694.6	1,532.2	787.0	5,754.9

* For the purposes of totaling, values shown in pentads 1910-14 and 1895-1899, for Queens and Staten Island, respectively, were grouped because inconsistencies in the fixed assets inventory made it impossible to assign pipe segments to earlier pentads.

** Pre-1899.

† Pre-1915.

†† Not available.

Table 2

Inventory of Mains by Diameter for Five Boroughs (miles)

Diameter (in.)	Bronx	Brooklyn	Manhattan	Queens	Staten Island	Total
4	0	0	1.2	0	0	1.2
6	58.0	219.0	71.0	85.7	31.0	464.7
8	320.5	929.1	10.7	814.0	490.2	2,564.3
10	0	0	0.7	0	0	0.7
12	356.1	348.3	445.7	407.7	178.6	1,736.4
16	4.5	97.6	2.3	24.9	26.3	155.6
20	76.8	163.5	67.3	94.0	29.6	431.2
24	2.2	11.7	1.1	11.8	14.9	41.7
30	0.3	19.3	12.0	17.0	1.0	49.6
36	18.7	9.7	28.8	9.1	2.1	68.4
48	29.4	37.1	51.1	37.8	7.7	163.1
54	0	0.1	0	0	0.2	0.3
60	0	21.8	0.9	13.6	2.7	39.0
72	0	17.4	0.5	16.6	2.7	37.2
Total	866.5	1,874.6	694.6	1,532.2	787.0	5,754.9

the numbers shown in the table do not reflect these efforts over the last 5 years. In general, 6-in. mains are being replaced with 8-in. pipes, except in Manhattan and highly developed parts of Brooklyn where 12-in. mains are being installed.

Water Main Break Rates

17. Data on break rates (in breaks/mile/year) for the five boroughs, based on a 25-year time period, are provided in Tables 3 and 4, by pentad and diameter, respectively. Trends in break rates according to pipe diameter are clear. Smaller pipes have a much higher break rate, and the break rate decreases for larger pipes. This aspect is true for all boroughs. The

Table 3

Break rate for Five Boroughs According to Pentad Laid

(Breaks/mile/year)

Pentad Laid	Bronx	Brooklyn	Manhattan	Queens	Staten Island
pre 1870		0.133	0.249		
1870-1874		0.036	0.181		
1875-1879	0.210	0.073	0.138		
1880-1884	0.437	0.042	0.245		
1885-1889	0.163	0.082	0.288		
1890-1894	0.184	0.049	0.258		
1895-1899	0.186	0.035	0.179		
1900-1904	0.104	0.025	0.182		
1905-1909	0.076	0.032	0.203		0.050
1910-1914	0.050	0.049	0.112	0.015*	0.023
1915-1919	0.098	0.130	0.149	0.089	0.010
1920-1924	0.108	0.049	0.260	0.044	0.043
1925-1929	0.104	0.053	0.223	0.064	0.039
1930-1934	0.053	0.093	0.142	0.058	0.019
1935-1939	0.046	0.062	0.135	0.080	0.018
1940-1944	0.062	0.051	0.301	0.038	0.009
1945-1949	0.078	0.123	0.196	0.041	0.006
1950-1954	0.051	0.029	0.296	0.031	0.007
1955-1959	0.066	0.038	0.273	0.050	0.003
1960-1964	0.056	0.067	0.425	0.103	0.018
1965-1969	0.034	0.026	0.426	0.080	0.013
1970-1974	0.008	0.004	0.340	0.013	0.006
1975-1979	0.018	0.006	0.181	0.012	NA**
Overall	0.075	0.053	0.167	0.056	0.029

* Pre-1915.
** Not available.

Table 4

Break Rate for Five Boroughs According to Diameter

(Breaks/mile/year)

Diameter (in.)	Bronx	Brooklyn	Manhattan	Queens	Staten Island
6	0.285	0.164	0.447	0.260	0.260
8	0.097	0.063	0.156	0.057	0.027
12	0.034	0.024	0.124	0.026	0.017
16	0.062	0.015	0.180	0.027	0.022
20	0.046	0.018	0.068	0.012	0.022
24	0.054	0.025	*	0.047	0.007**
30	*	0.012	0.078	0.021	
36	0.026	0.006	0.072	0.013	
48	0.016	0.010	0.037	0.048	
54	*	NA†	NA†	0.068	
60	*	NA†	NA†	0.036	
72	*	0.071	0	NA†	
Overall	0.075	0.053	0.167	0.056	0.029

* Not enough data to be statistically meaningful.
** Break rate for all pipes >20 in.
† Not applicable.

break rate for 6-in. pipes is extremely high, justifying the Bureau's decision to replace these mains.

18. Two boroughs stand out from the others as having substantially different break rates: Manhattan and Staten Island. Manhattan's is much higher, averaging 0.167 breaks per mile per year, while Staten Island's is much lower, with an average of 0.029 breaks per mile per year. The rate for Manhattan is two to three times higher than those for the Bronx, Brooklyn, and Queens, and almost six times higher than Staten Island.

19. Over time, the number of breaks that have occurred has increased. One example is Manhattan, where during the 5-year period between 1950 and 1955 there were 305 breaks. By comparison, during the 5-year period between 1971

and 1976, there were 482. The break rate in Manhattan is not, however, increasing as fast as that for the other boroughs. Corrosion tends to be responsible for increasing rates. In Manhattan, other causes have a much greater effect than corrosion. In addition, the break rate for Manhattan was so much higher to begin with. The effective annual increases in break rates for the five boroughs (percent increases) for the period between 1940 and 1979 are shown below:

Brooklyn	2.5
Bronx	2.2
Manhattan	0.6
Queens	2.9
Staten Island	3.8

The high rate of increase for Staten Island might be attributed to an increase in surface loading associated with increased urbanization in recent years. In addition, its initial break rate is much lower than the other four boroughs. Staten Island and Queens have unusually high break rates for pipes laid during the 1960's. This fact is probably due to either some batches of poor pipe or to poor construction practices used during this period.

20. Further statistical analyses were performed on the break rate data (from 1933 on) for the boroughs of the Bronx, Queens, and Staten Island. Non-linear aging equations were tested to determine the increase in break rate with time. In all three cases the data best fit the following equation:

$$J = a \exp(b(t - 1933)) \tag{1}$$

where:

J = break rate in year t, breaks/yr/mile

a = regression coefficient (expected break rate in 1933), breaks/yr/mile

b = rate of increase of breakage, 1/yr

t = time, years

Regression analyses determined the following constants for the three boroughs:

Borough	a	b
Bronx	0.036	0.018
Queens	0.022	0.024
Staten Isl.	0.017	0.024

Analyses were also performed on pipes installed in specific pentads, to determine the aging rate (the rate at which the break rate for that category of pipes changes with time). An equation similar to Equation 1 fit the data best:

$$J = a \exp(bt) \tag{2}$$

where the parameters have the same meaning as defined earlier, except that in Equation 2, t represents the age for the category. In this case the following values resulted:

Borough	a	b
Bronx	0.033	0.020
Queens	0.031	0.010
Staten Island		
(1910-19)	0.007	0.024
(1920-29)	0.003	0.057
(1930-39)	0.007	0.020

Factors Affecting Break Rates

21. There are any number of factors that can contribute to an increased break rate. In general, the effect of these factors appears to be uniform across all five boroughs, with some exceptions. The type of pipe that was installed in the city before 1970 is almost exclusively cast iron. Before 1930 it was unlined and after that date it was cement lined. In some cases large diameter pipes are made of steel or prestressed concrete. The total mileage of these types, however, is very small. Different manufacturing processes of cast iron pipe can account for differences in the durability of pipes. For example, horizontally cast iron pipe, which tended to have uneven pipewall thickness, was made before 1870. The effect of different types of pipe is hard to distinguish, however, because the year in which the pipe was laid could easily have been many years after the pipe was purchased. This situation resulted from the fact that the Bureau of Water Supply often bought pipe in large quantities and stockpiled it for use at a later date.

22. Even though ductile iron pipe has been used since 1970, there is still an overwhelming majority of cast iron pipe in the ground. In Manhattan, roughly 66 percent of the pipe in the ground today is unlined cast iron pipe and only 5 percent is ductile iron.

23. Periodically, poor batches of pipe or poor construction practices contribute to increased break rates. For example, in Brooklyn excessively high break rates were observed for pipes installed during two periods: 1915-19 and 1945-49. In both cases, it is possible that war-time shortages of iron resulted in low quality pipe material. This possible cause, however, should affect all boroughs equally, assuming that the same proportional lengths of mains were laid in all boroughs. It does not appear that there was significantly greater installation in Brooklyn during either of these periods, leaving the question unresolved. Poor construction techniques can be an important factor in a pipe's integrity. However, this aspect is very hard to document. The presence of ledge rock in the Bronx may be linked to poor construction, since the rock makes installation more difficult.

24. Construction activity near in-place pipes is also an important factor. In all boroughs this facet was very important, and it can, in some cases, explain geographic patterns associated with breaks. Higher break rates in lower and mid-Manhattan might be explained by a higher level of "activity," of which one aspect is frequent construction. In general, attempts to relate geographic factors (other than corrosive soil) to higher break rates were inconclusive.

25. The type of break that is observed by repair crews can help identify the cause of the problem. Unfortunately, this information is often missing from the reports completed at the time of the break repair. For the information that is available, circumferential breaks are more common on smaller diameter pipes, while longitudinal breaks are more predominant on larger diameter pipes.

26. The effect of frost on pipes is an obvious factor in break rate patterns, and all of the boroughs showed a pronounced increase in break rates during the winter months. The data for pipes larger than 12 in. in Staten Island, however, did not conform to this trend; break rates were actually higher during the summer months. This inconsistency lends support to the supposition that internal forces may be an important factor in this borough.

27. Corrosive soil and contact with other structures also cause breaks. In Brooklyn, analysis of the relative locations of corrosive soils and breaks reveals that the break rate for these areas is twice as high as the average for the borough. In the Bronx, contact with other structures and poor bedding are important factors, particularly when compared to the Queens, an otherwise similar borough. The greater incidence of contact can be explained by two facts: there is a higher concentration of subway lines, and there is more ledge rock.

28. This part has provided a brief summary of the characteristics and conditions of distribution systems in the five boroughs of New York City. Manhattan and Staten Island have systems whose conditions are notably different than the norm for the entire city. Manhattan's system, which is much older and subject to greater stress, has a high break rate. Staten Island has a newer system and a much lower break rate.

Collection of Break Data

29. The key to the analyses in the five volumes of the New York Infrastructure Study was the data base containing pipe break records. This was assembled by BCM and contained records of each break over a 25-year period. The Bureau of Water Supply needs to obtain these files and update them as an aid in decision making.

30. The Bureau would be wise to establish a way of retrieving records of pipe breaks from existing computerized data bases used by the City. It may even be necessary to set up a separate data base for break records. Such information should be kept in a useful form and be incorporated into the decision-making process for individual pipe replacement.

31. Each pipe break event is a way in which the distribution system reveals information about its condition. Periodic analysis of such data can provide insights into the causes of breaks and the efficacy of ongoing break replacement policies.

32. A pipe break data base needs to be developed in a way that it can be used for analysis of historical records to make decisions about pipe replacement. A decision to set up such a data base also brings with it a commitment to maintain the data base, including a screening of the data entered. Ideally, data entry can be tied with routine work order tracking.

PART III: SIMULATION MODEL

Overview

33. Part I of this report stated the premise upon which the choice of a replacement strategy should be based; that a certain level of pipe replacement will yield a least-cost strategy. To determine a least-cost strategy, several approaches must be evaluated. Performing these calculations several years into the future and discounting costs for each strategy allows comparison of the present worth of each approach. To accomplish the task, a simulation model was formulated and programmed to be solved on a computer.

34. Results for different strategies can be compared to each other and also to the results for the current strategy, which was adopted in 1970. The current strategy is to replace a water main segment if it has had two or more breaks over its history. Other possible strategies could be more aggressive (i.e., replace a pipe if it has had one break) or more passive (i.e., replace a pipe if it has had three, or more, breaks; or even, replace no mains). In addition, a totally different approach could be taken, such as replacing a fixed percentage of the system, with the possibility of concentrating on categories of pipes that have higher break rates.

35. The simulation model approaches the problem 1 year at a time, determining the number of main segments that should be replaced during that year for a given replacement strategy. Each borough is modeled individually, to see if different strategies will be best for the different boroughs. Main segments within each borough are categorized into bundles by pipe size and time period in which the pipe was laid. This delineation allows the use of different characteristics (break rates) for each bundle. The program determines break rates, applies a strategy, updates the break rate, and determines costs for each bundle. It then iterates through each bundle and year to provide an overall cost for each borough.

36. Figure 2 shows a general flowchart of the process. The first two boxes represent data input and manipulation of the data for use by the program. The data input routine prompts the user for parameter values to be used in the program. The manipulation routine arranges the data into a form that is compatible with the internal workings of the program and consistent with the parameter values entered by the user.

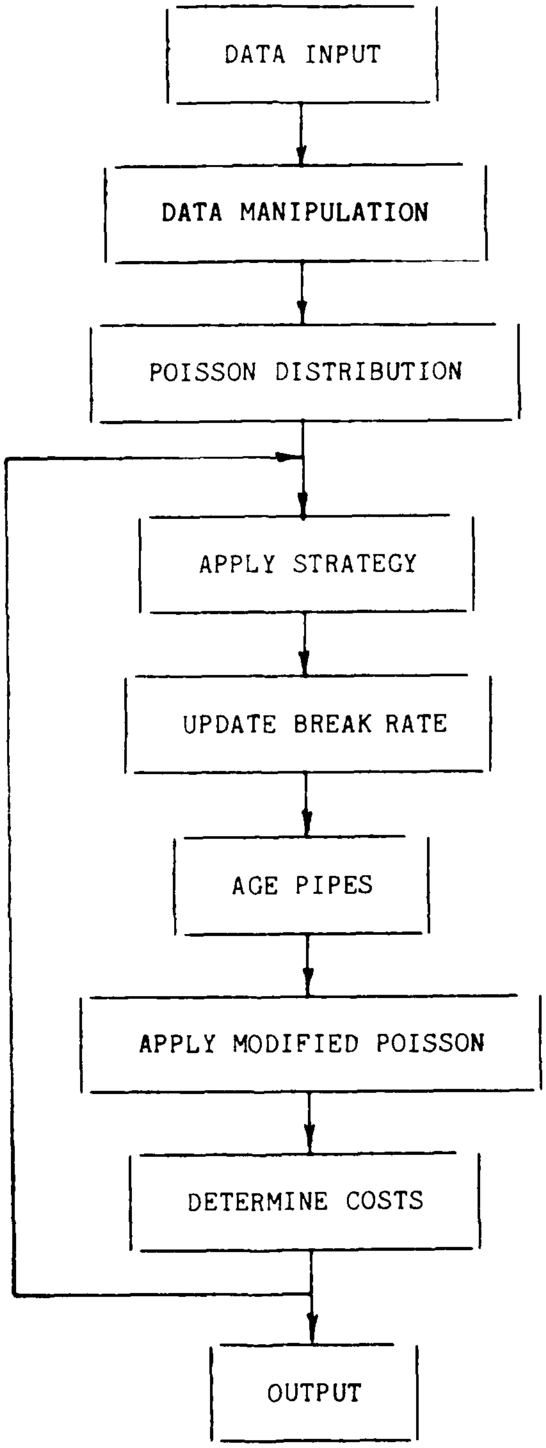


Figure 2. Flowchart of the simulation procedure

37. Since only mean break rates were available, the Poisson distribution is used to convert the mean break rate to a grouping of main segments with no breaks, with one break, etc. Following this calculation, a replacement strategy is applied to the "existing" pipe network to determine how many main segments should be replaced. Following the strategy subroutine, two subroutines change the characteristics of the pipes in the bundle. These include a subroutine that updates the break rate to conform to the revised network (with some high-break-rate pipes removed) and a subroutine that increases the breakrate of the pipes as they "age" in the system.

38. For subsequent years the Poisson distribution is applied in a modified manner, using the newly calculated average break rate to redetermine the number of main segments with 1, 2, etc. breaks. The costs of replacing old pipes with new and of repairing the in-ground pipes are determined in the next subroutine. At this point the procedure (from the strategy subroutine on) is repeated for each bundle of pipes. The final step prints the output of the entire procedure. All of these steps will be detailed below. In addition, Appendix A lists symbols that are used in the remainder of this chapter.

39. In the descriptions that follow, the term "main segment" will imply a length of pipe along the face of a typical city block. Although not all blocks are the same length, a uniform distance of 440 ft (1/12 of a mile) will be used as an average segment length. The terms "main segment," "pipe" and "block" are often used interchangeably in this report. Main segments are also grouped in different ways at different points in the program. An "age category" refers to a combination of main segments installed in a specific period of time (encompassing one or more pentads). In this report three age categories for existing mains are designated: old (laid before 1930), middle (laid between 1930 and 1970), and new (laid since 1970); in addition, there is a "future" age category that is created by the simulation for pipe laid after the initial year of the simulation. A "diameter category" is a combination of main segments of one or more diameters. Four categories are used in this report: 6-, 8-, 12-, and a combination of 16-, 20-, and 24-in. pipes. A "bundle" of main segments refers to a combination of main segments that are assumed to have similar characteristics. Bundles are delineated by borough, age, and diameter categories. For example, one bundle would consist of 12-in. mains laid between 1930 and 1970 in Brooklyn. In addition to the above

definitions, in the simulation main segments in one bundle are grouped according to the number of previous breaks; in other words, whether they have had zero, one, two, three, or four or more breaks. For example, the one-break group would refer to all mains in a particular bundle having had one break over their history.

40. One additional aspect that will help the reader follow the sequence of calculations is the fact that the simulation uses past data to predict future trends. Since the year-by-year data displayed wide variations (due to varying weather conditions, etc.) historical (cumulative) values were used (total breaks divided by total number of blocks). Since the simulation iterates on a yearly basis, annual break rates were determined each year based on the cumulative breaks at the beginning and end of each year.

Data Input and Manipulation

41. The data input section of the simulation accepts information on the distribution system, pertinent costs, and designated replacement strategy. Data on the distribution system are similar to those presented in Part II of this report. Only those mains up to 24 in. in diameter were included in the analyses, since large mains constitute a very small portion of the system.

42. The procedure creates bundles of mains, based on age categories (including one or more pentads) and diameter categories (including one or more diameters). All of the analyses reported in this document are based on categories resulting from the specification of three age categories (those laid before 1930, between 1930 and 1970, and after 1970), and four diameters (6-, 8-, and 12-in. mains and a grouping of 16-, 20-, and 24-in. mains). In other words, 12 bundles are utilized for each borough.

43. The length of mains in each bundle is determined by summing the lengths of pipe for the pentads and diameters making up the bundle. In addition, break rates are determined for each bundle using a weighted average (weighted by length of main). The length of main is then converted to a number of main segments, assuming that each segment is 440 ft long (1/12 of a mile). The break rates are then changed to a number of breaks per main segment over its history, based on the average age of each age group. Each main segment corresponds roughly to a block and its use as a basis for

replace/repair decisions corresponds to the Bureau's current rules for replacement of pipes with two or more breaks per block.

44. A sample calculation of a bundle break rate is presented below for the bundle that incorporates the three pentads following 1970 and 8-in.-diam pipes:

$$\begin{aligned}&\text{(bundle break rate, in breaks/block)} = \\ &[0.5\ \text{(break rate for 1970-1984 age category)} \\ &+ 0.5\ \text{(break rate for 8-in. pipe cat.)}]\ \frac{\text{ave. age of age category}}{\text{(12 blocks/mile)}}\end{aligned}$$

where the break rate for the age category is determined from the following formula:

$$\begin{aligned}&\text{(break rate, in breaks/mile/year)} = \\ &[\text{(break rate for '70-'74) (length of pipe in '70-'74 pentad, miles)} \\ &+ \text{(break rate for '75-'79) (length of pipe in '75-'79 pentad, miles)} \\ &+ \text{(break rate for '80-'84) (length of pipe in '80-'84 pentad, miles)}] \\ &\div \text{(total length in all three pentads)}\end{aligned}$$

45. Data for Manhattan had to be estimated, to a certain extent, since the available data were incomplete. BCM (1980) provided two tables of break rate data for Manhattan. One table accounted for all breaks that occurred between 1955 and 1978. The second table listed (by period of installation) those pipes that broke during the 1955 - 1978 period for which installation data were known. The period of installation of some of the mains that broke could not be identified and they were not included in the latter table. As a result, both tables were incomplete: the first because it only covered the 1955-1978 period and the second because it omitted mains whose installation date was unknown.

46. To reconcile this discrepancy, the two incomplete tables are manipulated to produce a complete table of estimated break rates. For example, 1,043 breaks of 6-in. mains were reported between 1955 and 1978. The period of installation was known for 473 of these mains and unknown for 570 of the mains. Nineteen mains were known to have been installed between 1870 and 1874. In addition, some of the 570 mains that broke between 1955 and 1978

were also probably installed between 1870 and 1874. The total number of breaks in the 1870-1874 period is calculated by:

$$(19)(1043/470) = 42$$

Similarly, there were probably mains that were laid in the 1870-1874 period and did not break in the 1955-1978 time span (22 years) but could have broken at some other time during their life (1874-1984, or 110 years). The 42 breaks are adjusted to account for the possibility that these mains broke in another period by:

$$(42)(110/22) = 210$$

47. In summary, in order to arrive at a realistic number of breaks for mains laid in the 1870-1874 period, the original number of breaks was multiplied by two ratios. One accounted for the fact that not all breaks could be identified with their main's period of installation. Another ratio accounted for breaks that occurred outside of the 1955-1978 period. Numbers of breaks for other pentads were estimated in a similar manner.

48. The manipulation section results in two arrays for each borough: a break rate for each bundle (in breaks per main segment over its history) and the number of main segments for each bundle. Although new pipe installation (not replacement) continues in the city, particularly in Staten Island, these additions are not considered. The simulation maintains a fixed length of mains throughout the simulated time period.

Poisson Distribution

49. The data available for the study included only the average number of breaks per main segment and were not detailed enough to identify the number of main segments that had experienced different numbers of breaks. The Poisson distribution was used to estimate the desired information by converting the average break rate into a pipe break distribution of main segments with no breaks, with one break, with two breaks, with three breaks, and with four or more breaks over its history.

50. The Poisson distribution is expressed as:

$$P(x) = \frac{u^{x} e^{-u}}{x!} \tag{3}$$

where: P(x) = the probability of having x breaks in a main segment, for the life of the main

e = the base of the natural logarithms

u = the mean number of breaks in a main segment for the life of the main, for the bundle, (breaks per main segment)

x = number of breaks in a main segment for the life of the main

51. The Poisson distribution is appropriate when the number of chances for the occurrence of an event (a break) is very high and the probability of the occurrence of one break is very low. Application of the Poisson process to the problem of pipe breaks is slightly different because the problem has two dimensions: space and time. In other words, the opportunity for a break to occur is distributed spatially, along the length of all the pipes in the system, and also distributed temporally (i.e., any one spot on a pipe could experience one or more breaks throughout its history). Since both time and the length of pipe are continuous, this means that theoretically there are an infinite number of chances for an occurrence and the probability of a single occurrence at a particular point and time approaches zero.

52. For the Poisson distribution to be valid, several characteristics of the data set must be satisfied:

a. The data must represent a counting process, which means that: (1) no breaks occur exactly at time zero, (2) the number of breaks at any specific place and point in time must be either one or zero, i.e., half a break is infeasible, (3) the number of breaks between any points in time and in space must be an integer value, and (4) for any non-overlapping sequence of time intervals or any non-overlapping pipe lengths, the number of breaks in the sum of the intervals or lengths is equal to the sum of the number of breaks in all of the intervals or lengths.

b. The data must have independent increments. For any length of pipe, the occurrence of a break in one length (or time span) is independent of the occurrence in any other length (or time span).

c. The data must have stationary increments. The number of breaks for any length of pipe must not depend on where the length of pipe is.

d. The probability that a break will occur at a fixed point in space and time is zero. This does not mean that the probability for a very small length (or very small time span) is zero, but rather that the probability that a break will occur in a segment of zero length is zero. Therefore, the exact location in time and space cannot be predicted ahead of time.

53. Clearly, some of these properties are satisfied while others are not. The integer nature of breaks lends itself to satisfying the first property. The second property is satisfied since the occurrence of one break has no bearing on the occurrence of another. This aspect should not be confused with the fact that an external influence (for example, a deeply penetrating frost) may cause breaks in different parts of the system at the same time. The third property does not hold, in general, since break rates can be higher for certain pipes, both when addressing the data in terms of spacial location or location in time (i.e., the age of the pipe). This problem can be countered, to a certain extent, by grouping the pipes into bundles with similar characteristics. This has been done by addressing each borough separately, and by setting up bundles for pipe size and age. In addition, different break rates are used for pipes that have different numbers of breaks. Other factors that might have an effect beyond those just cited (such as nature of overhead use) cannot reasonably be accounted for in a study of this scope. Therefore the assumption will be that within each bundle (i.e., borough, pipe size, and age group) and for pipes that have had the same number of breaks previously, the likelihood of breakage is the same throughout.

54. The results of applying the Poisson distribution will be a grouping of main segments according to the number of breaks expected. For example, the average number of breaks over its history per main segment for 8-in. pipe segments laid between 1930 and 1970 in Queens is 0.1712332. (Note: Throughout this part very small numbers will be used to illustrate the procedure, requiring maintenance of several digits to the right of the decimal.) Since there are approximately 4,320 main segments in the borough, the results of applying the Poisson distribution are shown in the following table:

Number of breaks x	Probability of x breaks P(x)	Number of main segments with x breaks
0	0.8426251	3,640.1404
1	0.1442854	623.3129
2	0.0123532	53.3658
3	0.0007051	3.0460
≥4	0.0000312	0.1347

55. A table such as this is created initially for each bundle in each borough. This table is then manipulated in the following sections of the procedure.

56. Although it may seem unrealistic, non-integer values for the number of main segments are used throughout the routine. It should be remembered that the overall intent is to address the total cost of a replacement strategy, and not to worry about which specific main segments are to be replaced. Earlier reports on the five boroughs addressed replacement of specific pipe segments.

57. To test the validity of the Poisson distribution, data from Staten Island were obtained for a number of blocks having had one, two, three, and four or more breaks in the last 30 years for several different size mains. The length of the rest of the mains that had never broken can be calculated by subtracting the length that have had breaks from the total length. Using this information, a break rate was calculated for each diameter. Using the Poisson distribution and the calculated break rate (u), the probabilities of having zero, one, two, three, and four or more breaks were calculated for each diameter. These probabilities were then multiplied by the total length of mains of each diameter to obtain the length of mains with zero, one, two, three, and four or more breaks. The actual lengths and the lengths calculated with the Poisson distribution are shown in Table 5 for each diameter main.

58. By inspection it can be seen that the Poisson distribution mimics the actual situation fairly well. The hypothesis that the data can be represented by the Poisson distribution cannot be proven with a chi-squared test since the number of observations for the higher break groups is very small (Walpole 1974). On the basis of the above analysis and the fact that similar events have been simulated using the Poisson distribution, this distribution predicts the occurrence of breaks adequately.

Table 5

Actual and Predicted Lengths of Water Mains Having Had 0, 1, 2, 3, and 4 or More Breaks in Staten Island (blocks)

Number of Breaks	8-in.		12-in.		16 to 24 in.	
	Actual	Simulated	Actual	Simulated	Actual	Simulated
0	5,611	5,533.7	2,054	2,050.1	826	815.7
1	213	337.7	83	90.9	17	32.7
2	39	10.3	6	2.0	2	0.7
3	6	0.2	0	0.03	3	0.009
≥4	11	0.003	0	0.0003	1	0.00009

Replacement Strategies

59. The core of the simulation is the application of a policy, or strategy, for replacing main segments. The strategy designates removal of certain groups of main segments; hence the table created using the Poisson distribution is revised according to different prespecified criteria. Two types of strategies can be applied:

Type I - all mains in a bundle having had x or more breaks are replaced (x can equal 1, 2, 3, or 4)

Type II - the worst y percentage of mains in a bundle are replaced

60. Type I strategies include the current approach (replace all mains with two or more breaks) and could result in replacement of very many or very few mains depending on the strategy applied and the distribution of sizes in the bundle. Type II strategies replace a specified percentage of mains in the bundle, starting with the worst ones. In all cases, a do-nothing (DN) strategy can be tested where mains are not replaced, but simply repaired as they break.

61. At this point one distinction should be made to allow a clearer description of how the procedure works. Pipe replacement consists of two steps: (a) removal of a main segment (from one of the age categories) and (b) relaying a new pipe (in the "future" age category). The future age category represents all pipes laid in future years (those years simulated by the procedure). All mains laid in future years by the simulation represent replacements and not installation of new mains to serve growth. The strategy

section assumes that all pipes, except for 6-in. mains, are replaced with the same size mains. This assumption was made so that the costs incurred solely as a result of pipe breakage would be accurately represented. Mains often are replaced because of both high break rates and inadequate carrying capacity, in which case a larger pipe would be laid to replace a smaller one. The difference in cost between replacing with the same size pipe or a larger pipe (needed solely to increase carrying capacity) was not included, so that economics of the repair/replace decision could be addressed. The difference in cost represents upgrading rather than replacing.

62. One additional step is applied to be consistent with the Bureau's policy of replacing all 6-in. mains with larger pipes. The procedure removes a specified percentage of 6-in. pipes from all age categories and replaces them with 8-in. pipes in the future age category. The specified percentage is applied each year to the original number of 6-in. water mains. As a result, after a certain length of time, all 6-in. pipes will have been removed. For example, if 10 percent is the specified value,

$$(0.1) \times (\text{initial number of 6-in. mains})$$

would be removed each year, resulting in complete removal after 10 years.

63. Because New York City does not have unlimited funds, a budgetary constraint, which applies only to the cost of replacement, was added to the model. It is assumed that when a main breaks, funds are available and it will be fixed immediately. The budget constraint is applied in the following way: Before any type of strategy is applied, the length of main segments to be replaced in each diameter group is summed and multiplied by a cost per length, to get a total cost of replacement. This total cost of replacement is compared to the budget. If the cost of replacement is less than the budget the strategy is carried out as planned. If the cost is greater than the budget, only a part of the mains originally planned to be replaced are actually replaced.

64. The results of the strategy portion of the simulation will be the truncation of the tail end of the distribution created by using the Poisson equations. For example, if a strategy of replacing all main segments with two or more breaks was being tested, all applicable main segments would be removed

(assuming the budget is sufficient). The table shown on page 27 in the previous section would be revised to:

Number of breaks x	Number of main segments with x breaks
0	3,640.1404
1	623.3129
2	0
3	0
≥4	0

65. The pipes that replace those that have been removed are put into a "future" age category that is created in the simulation. This age category represents the pipes "laid" during the simulation. Therefore, the distribution of 8-in. pipes laid in Queens in the future (resulting from this manipulation only) is shown by the following table:

Number of breaks x	Number of main segments with x breaks
0	56.5466
1	0
2	0
3	0
≥4	0

The 56.5466 main segments represents the sum of those segments (in the 1930-1970 age group) with two, three, and four or more breaks that were removed as a result of implementation of the strategy. Other pipes may be added to this future bundle, since, for example, 8-in. pipes that are removed from the pre-1930 age group also would be included here.

66. Note that all of the newly installed pipes are expected to have no breaks immediately upon installation. This assumption will be relaxed by assigning a very small break rate to new pipes. This relaxation is done for two reasons. First, even new pipes have a non-zero (although very small) probability of breaking immediately after being laid. Second, all new pipes

will deteriorate with age, and to apply the aging equation (discussed below) a non-zero break rate must be used.

Update and Age

67. The update and age sections of the simulation modify the characteristics of the pipe bundles. The update section simply redetermines the average break rate for the bundle based on the characteristics of the main segments that were not removed in the strategy routine. The age section then "ages" (increases) the break rate according to a specified equation. Figure 3 shows an exaggerated plot of the break rate over a 1-year increment. The figure shows three possible strategies: (a) moderate, (b) aggressive, and (c) do nothing. The strategy and update procedures are treated as if they occur at the beginning of the year. The drop in the break rate represents the upgrading of the system. Note that for the do-nothing case there is no drop. Between the beginning and end of the year, the break rate increases according to an aging equation, resulting in a higher break rate at the end of the year.

68. In the update routine, the average break rate is determined by simply weighting the break group (zero, one, two, etc. breaks) by the number of main segments in each group. Therefore, the new average would be:

$$u' = \left[\sum_{i=0}^{4} iN_i\right] \div \left[\sum_{i=0}^{4} N_i\right] \tag{4}$$

where: u' = revised break rate (breaks/block) following application of strategy

i = the number of breaks for the break group

N_i = the number of main segments with i breaks in break group

Using the numbers from the example in the preceding section the new break rate would be:

$$u' = \frac{(623.3129) \times (1)}{3{,}640.1404 + 623.3129} = 0.1462 \text{ breaks per block}$$

This value represents the average rate at which those main segments from the current bundle that were left in the ground will break.

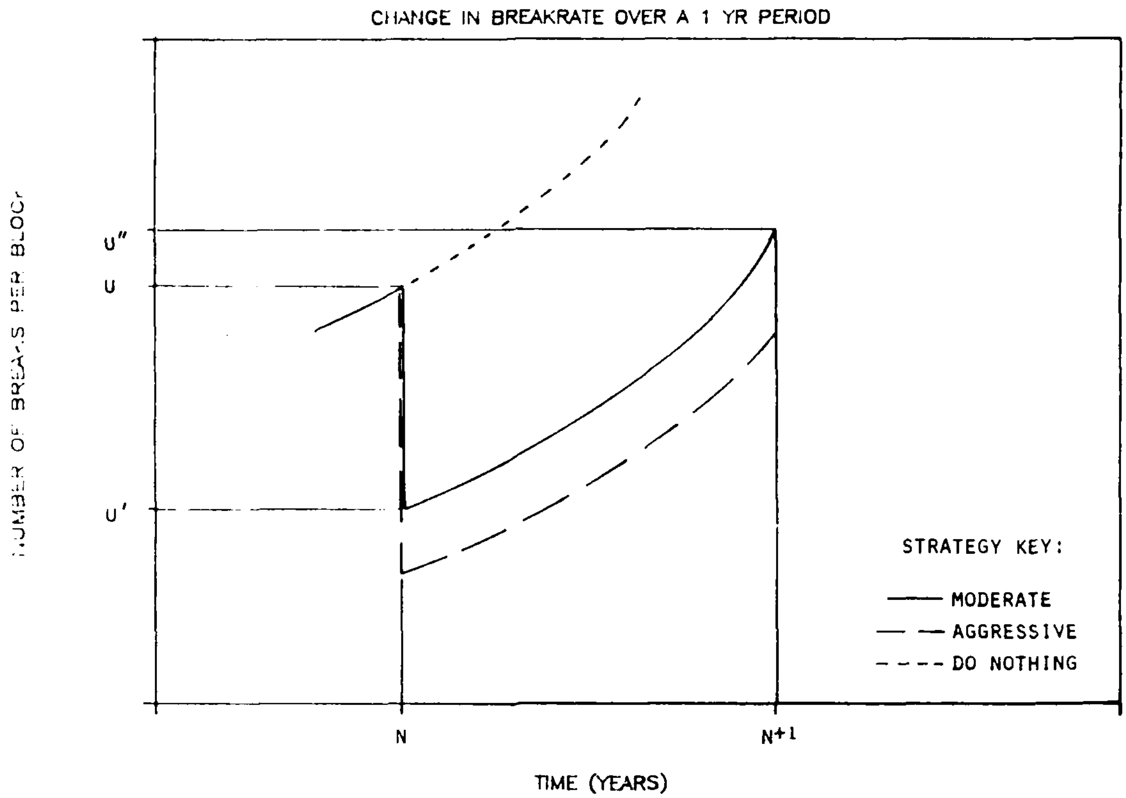


Figure 3. Change in break rate as a result of three different strategies

69. When applying Equation , a value of i = 4.0 would normally be used to represent the pipes with four or more breaks. Use of this value will sometimes cause the update routine to slightly underestimate the actual break rate. This situation only occurs when a small fraction of the mains are replaced with a type II strategy. In this case higher values were used to represent the break rate for the four-or-more break group. These numbers, shown below, were chosen so that if a very small fraction of the system was replaced each year, the do-nothing strategy would be approximated.

Borough	Value
Bronx	6.045
Brooklyn	5.700
Manhattan	6.616
Queens	5.546
Staten Island	5.250

70. Since these main segments will deteriorate with age, this newly calculated break rate must be revised to reflect this fact. The age section of the simulation determines the new rate based on an aging equation determined by Walski and Wade (1987) using data from the Bronx, Queens, and Staten Island. It is:

$$u'' = u' e^{bt} \tag{5}$$

where

u'' = the break rate after aging (breaks/block)

71. Equation 5 would not be viable for pipes with a zero break rate. Therefore, all new pipe is assigned a low break rate (.001 breaks/block/year) when it is installed. Selection of this value is discussed in the next part of this report.

72. Studies of New York City data indicate that the break rate has increased by about 2 percent per year. However, because of better materials and construction practices, it is anticipated that newly installed pipe will deteriorate at a less rapid rate. To account for the discrepancy in rates, different values of b are used for different age groups. For all pentads before 1970, $b = 0.04$ years^{-1}. For pipes laid after 1970, $b = 0.02$ years^{-1}. Determination and justification of these values can be found in the next part of this report.

73. For the example numbers used above and a value of $b = 0.04$ years^{-1}, the break rate (after aging has been accounted for) is:

$$u'' = 0.1522 \text{ breaks per block}$$

74. The last step in this section determines the annual break rate for the current year of the simulation. This rate is later used to determine the expected number of breaks during the year. The annual break rate w is simply the difference between the break rate at the beginning and end of the year, divided by the time period (1 year):

$$w = u'' - u' = u'e - u'$$

or

$$w = u' (e^b - 1) \qquad (6)$$

where: w = the mean number of breaks in a main segment in a year, for the bundle (breaks per main segment per year)

Figure 3 shows a schematic of the relationship of u' and u".

75. Following through with the example calculations using Equation 6, w = 0.0059665 breaks/block/year (J = 0.072 breaks/mile/year).

Modified Poisson

76. At this point the procedure has determined a new break rate based on the facts that: (a) poorer main segments were removed from the bundle, and (b) those that were left deteriorated somewhat over the 1-year time increment of the simulation. The new annual break rate (w) is now used with the Poisson distribution to again determine the distribution of main segments with zero, one, two, etc. breaks. The Poisson equation cannot be applied using the historical break rate (u") since the application is for a 1-year period. The result would likely be a recalculated break rate that is lower than the previous one, and would therefore yield a number (of main segments with zero breaks) greater than had been present in the first place. This situation is impossible since no new pipes have been laid for this bundle (e.g., those 8-in. pipes laid in Queens between 1930 and 1970).

77. In addition to the above difference, the Poisson distribution is now being applied each year of the simulation. As a result, the break rate must be expressed on a yearly basis. To avoid confusion, different symbols will be used for this case. Restating the Poisson distribution:

$$P'(y) = \frac{w^y e^{-w}}{y!} \qquad (7)$$

where:

P' (y) = the probability of having y breaks in a main segment in 1 year

y = the number of breaks during one year

78. The Poisson distribution must now be used to predict the number of new breaks in the current year for each different break group (i.e., the pipe group with no breaks, the pipe group with one break, etc.). Additional break(s) must be added to the number that have occurred thus far in the simulation. To do this the Poisson distribution must be applied to each break group in each bundle. For example, for those main segments that have had one break, the probability that zero breaks will occur means that some of the main segments will still have one break. In addition, for the same group of mains (that have had one break), the probability of one more break means that a certain number of the mains will now be expected to have two breaks. This same reasoning must be applied to each break group.

79. Evidence has shown that those pipes that have had one or more breaks have a much higher break rate than those that have had none (Walski and Pelliccia 1982, Clark, Stafford, and Goodrich 1982, Shamir and Howard 1979). To account for this fact, those pipes that have had one or more simulated breaks are assigned higher break rates. This task is accomplished by designating a "higher break factor" for the pipe groups with one or more breaks. This factor, f_i , is defined as the ratio of the break rate for pipes having i breaks to the break rate for pipes having had no breaks. Since the break rate for the bundle is known, the break rate for the zero-break group (and therefore the other break groups) can be determined once the higher break factors are assigned. The following equation illustrates the approach:

$$w = \left[w_o \sum_{i=0}^{4} N_i f_i \right] \div \left[\sum_{i=0}^{4} N_i \right] \qquad (8)$$

where

w_i = break rate for break group i

w_0 = break rate for the zero-break group (breaks/block/yr)

f_i = high break factor for break group i (i = 0...4) (f_0 = 1)

From Equation 8 the break rates for the zero-break group can be determined:

$$w_0 = \left[w \sum_{i=0}^{4} N_i \right] \div \left[\sum_{i=0}^{4} N_i f_i \right] \qquad (9)$$

and the break rate for groups with more than one break can be found using Equation 10.

$$w_i = f_i w_0 \qquad \text{for } i = 1, 2 \ldots 4 \tag{10}$$

80. The example from above can be used to illustrate this approach. The break rate resulting from the age section of the simulation was an annual rate ($w = 0.0059665$ breaks/block/year). Using this rate and higher break rate factors of $f_1 = 5$, $f_2 = 10$, $f_3 = 15$, and $f_4 = 20$, the break rate for the zero-break group can be determined using Equation 9:

$$w_0 = 0.0037648$$

From this break rate, the other group break rates are determined:

$$\begin{aligned} w_1 &= f_1\, w_0 = 5(0.0037648) = 0.0188242 \\ w_2 &= f_2\, w_0 = 10(0.0037648) = 0.0376480 \\ w_3 &= f_3\, w_0 = 15(0.0037648) = 0.0564726 \\ w_4 &= f_4\, w_0 = 20(0.0037648) = 0.0752967 \end{aligned}$$

81. When the Poisson distribution is applied to each break group, the appropriate break rate is used in the Poisson equation. For example, w_1 is used in Equation 7 when it is applied to break group one, w_2 is used for break group two, etc.

82. The process is illustrated below, using the example developed earlier, where there were 3,640.1404 mains having had no breaks and 623.3129 mains having had one break.

Number of additional breaks, y	Probability of y new breaks P'(y)	Number of total breaks z	Number of zero-break main segments with z breaks
0	0.9962423	0	3,626.4618
1	0.0037507	1	13.6531
2	0.0000071	2	0.0257
3	0	3	0
≥4	0	≥4	0

83. A similar determination must now be performed for those main segments that have had one break (623.3129 of the original 4,320 main segments). Now, however, the segments with additional breaks are determined. The following table summarizes the results of the calculations.

Number of additional breaks, y	Probability of y new breaks P' (y)	Number of total breaks, z	Number of one-break main segments with z breaks after 1 year
-	-	0	0
0	0.9813519	1	611.6893
1	0.0184732	2	11.5146
2	0.0001739	3	0.1084
3	0.0000011	≥4	0.0007

84. The right-hand columns of each of the above tables represent the number of main segments from the break group that are expected to have the indicated number of breaks. Since the distribution resulting from the strategy routine had main segments in only the zero- and one-break groups, the sums of the numbers in the right-hand columns will represent the main segment in each break group for all of the main segments in the category. That sum is shown below:

Number of breaks x	Number of main segments with x breaks
0	3,626.4618
1	625.3424
2	11.5403
3	0.1084
≥4	0.0007

85. Once a table similar to the one shown above has been created for each bundle, the simulation proceeds and increments the process by 1 year and then repeats the strategy, update, age, and modified Poisson subroutines. Figure 4 shows the changes that are made in the characteristics of a bundle of mains in graphic form, using the numbers from the previous example.

Cost Determination

86. Two major cost components are crucial to the results of the simulation. These are the cost of replacing mains and the cost of continuing to repair main breaks. Other costs are certainly relevant to the overall

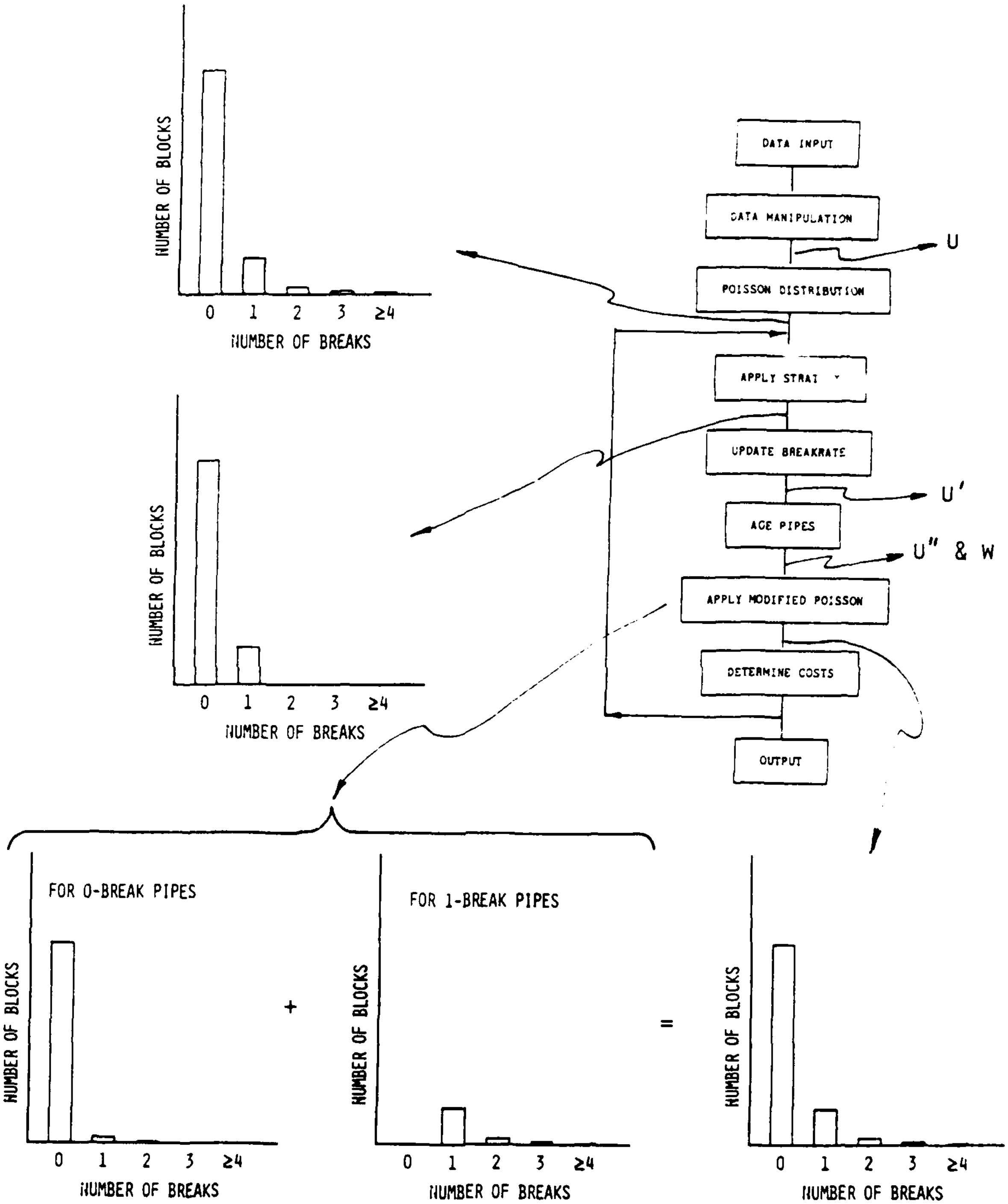


Figure 4. Flowchart of procedure showing changes in distribution of pipe breaks

process; however, they are either insignificant or are fairly uniform for all potential strategies.

87. Replacement costs are determined by applying unit replacement costs (in \$/length of main) to the number of blocks that have been removed from any of the past age categories and installed in the future age category. For the example values that have been used throughout this part (8-in. main segments laid between 1930 and 1950 in Queens), 56.5466 blocks were replaced in the strategy subroutine. Therefore, assuming a unit cost of \$90/foot, the replacement cost is:

$$(\$90/\text{foot})\ (440\ \text{feet/block})\ (56.5466\ \text{blocks}) = \$2{,}239{,}245$$

88. Repair costs are determined by applying unit costs (in \$/break) to the number of breaks expected for in-place pipes during the simulated year. The number of expected breaks is determined from the break rate for the bundle and the number of mains in the bundle. The number of breaks for the example is therefore:

$$\begin{aligned}(0.0059665\ \text{breaks/block/year}) \times (4{,}263.4533\ \text{blocks})\\ = 25.4379\ \text{breaks/year}\end{aligned}$$

89. In general the unit cost of a break includes only the direct cost of break repair, and does not include indirect costs that are also borne by the city. These include costs such as disruption of services, police overtime, damage to other city property, liability, etc. These costs are very difficult to quantify and have been accounted for with the use of a multiplier, called an indirect cost factor (ICF).

90. Following through with the example, and assuming a repair cost of \$5,000 per break and an ICF of 2.0 (i.e. an additional \$5,000 per break for indirect costs), the cost of repair for the current year is:

$$(2.0)(\$5{,}000/\text{break})(25.4379\ \text{breaks}) = \$254{,}379$$

91. The reader should remember that this example represents the costs for only one bundle consisting of 4,320 blocks and for only 1 year of the simulation. In addition, the break repair cost for 8-in. pipe might be lower

than for larger pipe sizes. A similar analysis for, say, 12-in. mains would likely yield a much higher cost, depending on the break repair cost that is used.

92. All costs are tabulated for each iteration (year) of the simulation. The present value of costs for each year is also determined, and the sums of the present values for all years are added to determine the overall cost of the relevant strategy.

PART IV: ANALYSES

93. This part of the report describes various aspects of the project that relate more specifically to New York City. Part III described the simulation model in a somewhat generic sense; even though the procedure was tailored to New York, it could be used to analyze other distribution systems with similar characteristics and background data. In addition, this part presents data that were used in the analyses, the results of which are presented in the next part.

Selection of Parameter Values

94. Preliminary analyses were conducted to determine appropriate values for relevant input parameters, including: (a) the aging rate, (b) the initial break rate, and (c) the higher break rate factors. Results of sensitivity analysis for the initial break rate showed that as long as the initial break rate for new pipes was relatively low, its value had only a minimal effect on the overall results. A value of 0.001 breaks per year per block was used throughout the following analyses. Varying the higher break factors also produced only minor changes in the overall results. This is most likely explained by the fact that the number of pipes with a high number of breaks is extremely small and therefore does not contribute greatly to the final result. Values of 5, 10, 15, and 20 were used for those pipes with one, two, three, and four breaks, respectively. In other words, a pipe that has had two breaks over its history is assigned a break rate 10 times higher than a pipe that has had no breaks.

95. The aging rate is an important factor since it dictates how quickly the break rate increases from year to year. Results of previous studies (Walski and Wade 1987) have shown that an increase of a little over 2 percent per year is representative of the city. This value, however, represents not only those pipes that have been in the ground since installation, but also those that have been laid as replacements. The simulation program, however, does not group the previously laid and newly laid mains in the same bundles. Therefore, a higher aging factor for the "unreplaced" pipe segments should be used. This relationship is shown in Figure 5, where the curve labeled "none replaced" represents the bundle with no new pipes installed, and the

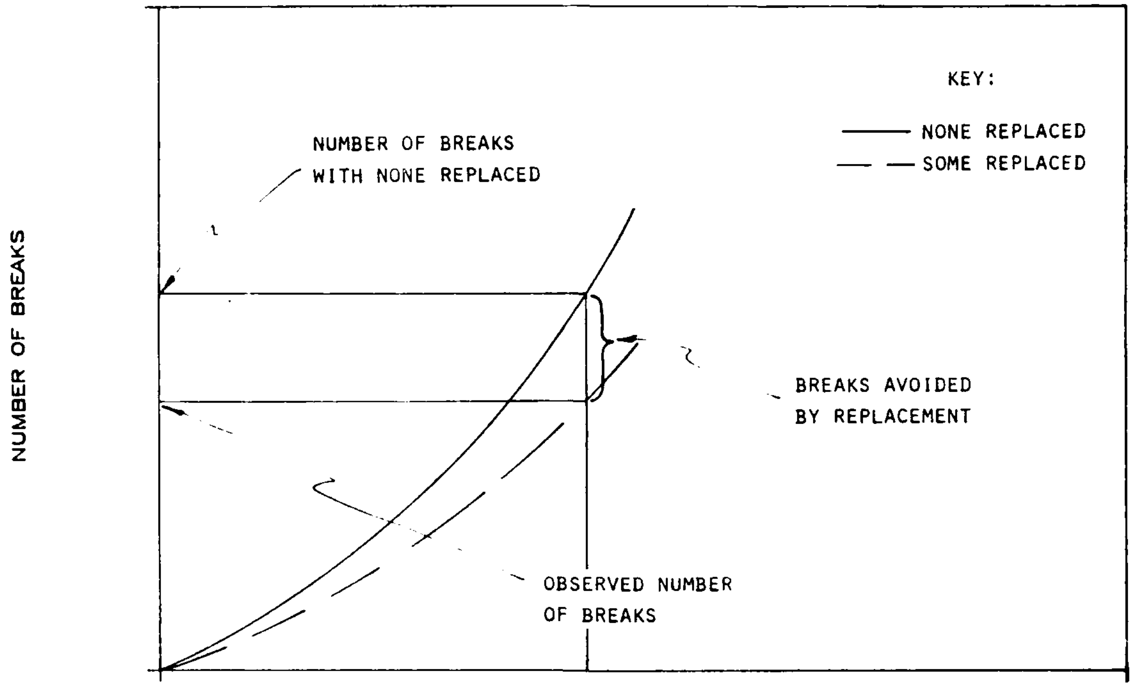


Figure 5. Relationship of break rate aging for pipe bundles with and without replacement

curve labeled "some replaced" represents the same bundle as it would have been observed over history (with new pipes being installed periodically). Assuming that the number of breaks in new pipe is negligible, the two aging rates can be related in the following way:

$$\left[\begin{array}{c}\text{Actual number}\\ \text{of breaks}\\ \text{observed}\end{array}\right] = \left[\begin{array}{c}\text{Number of breaks}\\ \text{with none}\\ \text{replaced}\end{array}\right] - \left[\begin{array}{c}\text{Number of breaks}\\ \text{avoided by}\\ \text{replacement}\end{array}\right] \tag{11}$$

If:

B_h = the number of breaks over history (observed)

B_n = the number of breaks for the bundle if pipes were removed and none were replaced

N = the number of blocks in the bundle initially

ΔN = the number of blocks removed from the bundle for replacement

u_o = the initial break rate for the bundle (breaks/block/year)

u_R = the break rate of those pipes removed for replacement (breaks/block/year)

u_n = the break rate for the bundle when pipes are removed but none are replaced (breaks/block/year)

u_h = the break rate that is observed over history for the bundle (removed pipes are replaced with new pipes) (breaks/block/year)

b' = the aging rate for the existing pipes (with no new replacement) for the bundle (years^{-1})

96. Since the number of breaks over a time period is equal to the break rate times the number of blocks, then:

$$B_n = u_n \quad (N - \Delta N) \tag{12}$$

$$B_h = u_h \ (N) \tag{13}$$

In addition, u_n and u_h are related to the initial break rate u_o by the aging equation (Equation 5):

$$u_n = u_o \quad e^{b't} \tag{14}$$

$$u_h = u_o \ e^{bt} \tag{15}$$

97. Combining Equations 11 through 15, and considering a 1-year time period (t = 1.0), yields:

$$u_o e^b \ N = u_o e^{b'} \quad (N - \Delta N) - u_R \ (\Delta N) \tag{16}$$

Solving for the no-replacement aging rate b' yields:

$$b' = \ln \left[\frac{e^b + (u_R/u_o)(\Delta N/N)}{(1 - \Delta N/N)} \right] \tag{17}$$

Note that if $\Delta N = 0$, $b' = b$.

98. To solve for b', values for ($\Delta N/N$) and (u_R/u_o) must be known. Based on experience over the last 15 years, approximately 0.5 percent* of the system has been replaced each year. Therefore, $\Delta N/N = 0.005$. The value of u_R/u_o is much more difficult to estimate. It represents the ratio of the break rate for those pipes removed for replacement to the initial break rate of the pipes in the bundle. A value of 5.0 was assumed for this ratio. Using Equation 17, with values of $b = 0.02$, $u_R/u_o = 5.0$, and $\Delta N/N = 0.005$ results in a value of $b' = 0.0492$, or about 5 percent.

Verification and Calibration

99. To verify that the model is able to accurately predict future break rates, the program was used to predict the occurrence of breaks following 1970, using data up to that point in time. The year 1970 was chosen for two reasons: (a) it represents the point at which ductile iron pipe was first installed, and (b) it is about the time when the Bureau of Water Supply initiated its policy of replacing those mains that had had two or more breaks. This second aspect allowed the use of a policy in the model that was also implemented in the field.

100. To verify the model, two values resulting from the simulation were compared to those that actually occurred: the number of breaks and the number of mains that were replaced. The historical values for each borough were obtained from the Bureau in the form of values for each of the years between 1970 and 1985 for each borough, and the averages for the 15-year period were calculated. The simulated values were generated using two different strategies: (a) replace all mains which have had two or more breaks and 5 percent of 6-in. mains, and (b) replace all mains that have had three or more breaks and 5 percent of 6-in. mains. The policy of the Bureau since about 1970 has been to remove all mains that have had two or more breaks and to gradually remove all 6-in. mains. Strict adherence to this policy was probably unlikely in all years; therefore, the resulting action was probably to have removed some of the mains that have had two or more breaks, and almost all of

---

* Comments from the City of New York on the draft of this report indicated that approximately 1 percent of the system has been replaced each year since 1980. Half of these replacements have been 6-in. mains.

the mains that have had three or more breaks. In other words, somewhere between the two- and three-break policies. In addition, even if the two-break policy had been strictly adhered to, a lag time between the designation and removal of a pipe segment could be lengthy.

101. Using an aging rate of 5 percent for old pipes and an aging rate for new pipes of 2 percent per year, "projections" were made for the period from 1970 to 1985 using the two policies. The number of breaks resulting from the simulation were higher than those experienced during the 15-year period, therefore "projections" were made using an aging rate of 4 percent for old pipes. The results for analyses using 4 and 5 percent are shown in Table 6 along with the actual number of breaks observed for the five boroughs.

102. In addition to comparing the number of breaks, the number of replaced pipe segments during the 15-year period was determined. Table 7 shows the comparison of the two policies (each using an "old" aging rate of 4 percent and a "new" aging rate of 2 percent) and the average number of blocks that were replaced during the verification period. As can be seen in Table 7, the model replaces more than the length of mains that was actually replaced. This is a result of the large number of mains that are replaced in the first year of the simulation (i.e., catching up with the backlog of pipes that should have been replaced but were not). It is unlikely that such large replacements took place during the 15-year period. If the average length of mains replaced in the first year of the simulation is not included in the calculation, then the predicted length of replaced mains is much closer to the amount that was actually replaced. This scenario is shown in Table 8. With the first year included, the average length of mains replaced by the two- and three-or-more break strategies is 809.2 [(907.4 + 710.9)/2], which is 298.3 more than the actual number of 510.9. When the first year's replaced mains are not included, the average length of mains for the two-or-more and three-or-more strategies is 409.9 (432.5 + 387.7)/2], which is 101 less than the actual number of 510.9 replaced mains.

103. The third aspect to compare between the actual and the simulated cases is the trend of break rates over the 15-year period. It is difficult to detect any upward or downward trend in the actual data. The data appear to scatter around the average value. The trend in the simulated cases is a direct result of the combining of the amount of replacement and the number of breaks (which is directly related to the aging rate). When 5 percent of 6-in.

Table 6

Actual and Simulated Average Annual Number of Breaks for Verification Period for Alternative Aging Rates and Replacement Rules*

Borough	Actual No. of Breaks**	Simulation Results b = 0.04 ≥2	b = 0.04 ≥3	b = 0.05 ≥2	b = 0.05 ≥3
Bronx	74.1	71.1	107.3	113.9	136.0
Brooklyn	138.1	129.2	181.5	162.1	233.2
Manhattan	123.2	95.3	126.4	118.9	155.2
Queens	113.6	94.5	128.4	119.3	166.3
Staten Isl.	45.8	25.7	32.7	32.9	43.1
NYC Total	494.8	415.8	576.3	547.1	733.8

* All new-pipe aging rates = 2%

** Actual data represent averages of 15-year period, 1970-1984

Table 7

Actual and Simulated Average Number of Blocks Replaced for Verification Period*

Borough	Actual Length Replaced	Simulated length replaced: Two or More Strategy	Simulated length replaced: Three-or-More Strategy
Bronx	98	151.1	62.8
Brooklyn	111.7	212.1	162.5
Manhattan	76.0	411.4	393.9
Queens	194.3	103.9	70.4
Staten Isl.	30.8	28.9	21.3
NYC Total	510.9	907.4	710.9

* Aging rate for old pipes = 4 percent, aging rate for new pipes = 2 ,ercent

Table 8

Actual and Simulated Average Number of Blocks Replaced For All But First Year of Verification Period

Borough	Actual Length Replaced	Simulated Length Replaced: Two-or-More Strategy	Simulated Length Replaced: Three-or-More Strategy
Bronx	98.0	71.2	60.6
Brooklyn	111.7	189.1	162.2
Manhattan	76.0	53.6	72.6
Queens	194.3	91.5	70.5
Staten Isl.	30.8	27.1	21.4
NYC Total	510.9	432.5	387.3

pipes are removed, the two-break policy results in a decrease in the overall break rate (breaks per block). The three-break policy yields a less discernable trend, with the break rate for some boroughs decreasing while it increases for others. When 6-in. pipes are replaced on the same basis as other pipes and not according to a fixed percentage per year, the break rate does not decrease as much as in the previous cases. When a three-break policy is used, the break rate (breaks per block) increases. These simulated trends seem quite reasonable when compared with the actions taken and data observed for the 1970-1985 period.

104. The verification of the simulation provides as much confidence in its ability to model the system as is possible, given the uncertainties in some of the input data. Using values for the input data that were obtained either from previous reports or directly from the Bureau of Water Supply, or were approximated using reasonable assumptions, the simulation model does a fairly good job of replicating the actual data available for the simulation period without adjusting any of the parameters. The "predictions" supplied by the simulation were improved by calibrating the model. This calibration was done by adjusting the aging rate for old pipes in the system. Only a minor change was necessary in this rate (reducing it from 5 to 4 percent) to achieve good results.

Economic Aspects

105. The two primary costs in the simulation model are the cost of replacing pipe and the cost of repairing breaks. Replacement costs are expressed in dollars per foot of main laid, and repair costs include the direct cost (labor and materials for excavation, pipe repair, and road resurfacing) of repairing a break.

106. No universal agreement was apparent for assigning values to the costs, particularly the break repair costs. As such, analyses were performed with two sets of data. The first set, shown in Table 9, was taken from previous reports, and delineates costs according to pipe diameter.

107. The large discrepancy between the repair cost for 8-in. mains as opposed to the larger diameter mains is, presumably, because breaks in large-diameter mains are repaired by private firms on a contract basis. There is some disagreement, however, on whether the break repair values in Table 9 are reasonable.

108. The second set of data is shown in Table 10, and was obtained from personnel in the Bureau of Water Supply in the spring of 1988. Break repair costs were determined by averaging costs over all three pipe diameters. Conversations with several people in the Bureau supported use of a uniform value. Replacement costs in Table 10 are categorized by borough so that the effect of different costs in different boroughs can be investigated.

109. The model applies a budget constraint to each borough, based on a budget for the entire city apportioned according to length of main in each borough. New York City's budget projections for replacing 6- to 24-in. mains and the number of 6- to 24-in. mains replaced in past years were obtained from the Bureau. From this information, the annual budget for replacement was estimated at $60 million per year for the entire city. The budget for each borough was apportioned based on the percentage of its mains compared to the entire city. The annual budgets for replacement are shown in Table 11.

110. The model determines both repair and replacement costs for each year of the simulation, and discounts all costs to present value (year zero of the simulation). Choice of the discount rate can reflect anticipated inflation. When discounting future costs, an inflation-adjusted discount rate r is used (Hanke, Carver, and Bugg 1975):

Table 9

Average Water Main Repair and Replacement Costs*

Diameter in.	Replacement** Cost ($/ft)	Repair† Cost ($/break)
8	90	5,000
12	105	25,000
20	150	27,000

* Construction costs only, and do not include related engineering project costs

** Source: Walski and Wade (1987)

† Source: Betz, Converse, Murdock Inc., (1984)

Table 10

Average Water Main Repair and Replacement Costs Obtained from Bureau of Water Supply (1988 Dollars)

Diameter	Replacement Cost ($/foot)					Repair Cost
in.	Bronx	Brooklyn	Manhattan	Queens	Staten Isl.	($/break)
8	83	108	100	84	84	8,600
12	94	122	113	95	95	8,600
20	130	169	156	131	131	8,600

$$r = \frac{i - f}{1 + f} \tag{18}$$

where:

r = inflation-adjusted discount rate

i = discount rate

f = inflation rate

The results presented in the next part assume an inflation-adjusted discount rate (whenever discount rate is mentioned, it is the inflation-adjusted rate). It is easier to comprehend the meaning of the inflation-adjusted discount rate by addressing values for the discount and the inflation rates individually.

Table 11

Annual Replacement Budget for Boroughs

Borough	Length of Mains 6 to 24 in. in Diameter (miles)	Percent of Total*	Budget (Millions of Dollars)
Bronx	818.1	15.2	9.1
Brooklyn	1,769.3	32.8	19.7
Manhattan	599.1	11.1	6.7
Queens	1,438.1	26.6	16.0
Staten Isl.	770.5	14.3	8.5
			60.0

* Comments from the City of New York on the draft of this report indicated that these percentages are probably low for Brooklyn and Manhattan, where they have an intensive program of replacing 6-in. mains when constructing highways.

To ease this transformation, a plot of a relationship among the three rates is shown in Figure 6.

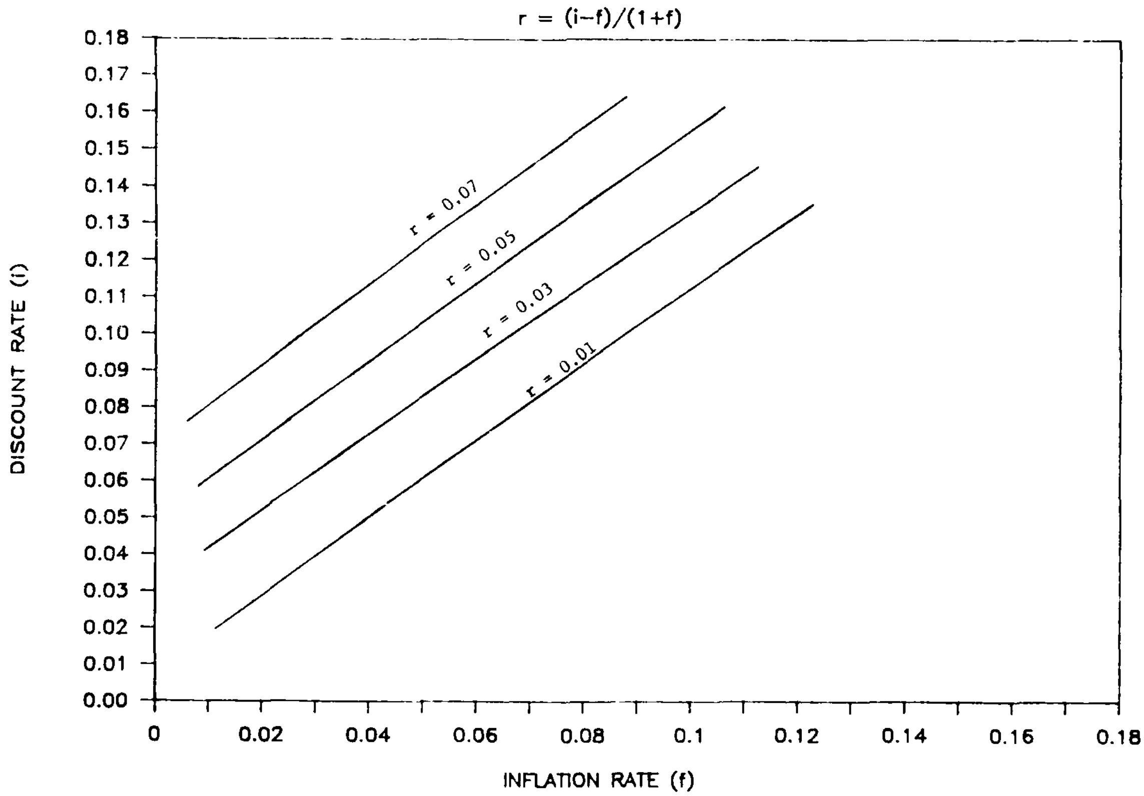


Figure 6. Determination of inflation-adjusted discount rate

PART V: RESULTS AND DISCUSSION

111. Numerous computer runs were made to analyze the costs associated with different replacement strategies and the resulting condition of the system. Given that several of the input parameters could be varied, the number of possible strategies that could be examined is enormous. Therefore, the results that are contained in this part are limited to those based on a realistic range of input parameters and/or those that were generally representative of the individual boroughs or of the city as a whole. Results for specific cases are shown for selected strategies for all boroughs and for the entire city. The effect of varying certain parameter values is demonstrated with either the results for the entire city or for a representative borough.

112. The results shown in the following sections are grouped to show: (a) the results for the general class of strategies that are based on replacement of pipe with a certain number of breaks, (b) the results for the general class of strategies that are based on replacement of a certain percentage of pipes, (c) application of different strategies to different diameter groups, (d) application of different strategies to different age groups, and (e) general observations. Sensitivity analyses are also presented with the results. Some results in this part show trends over the 50-year simulation period, starting in 1985. This year was used as the start of the simulation since data were unavailable after 1985. The results could easily be assumed valid for another beginning year, say, 1990, if one assumption is made; that the break rate data between 1985 and 1990 is approximately the same as that for the 1980 - 1985 period.

113. All of the results presented in this part involved a strategy that removed 10 percent of the 6-in. mains each year. Therefore, no 6-in. main segments remained following the tenth year of the simulation. Simulations were performed for different ICF values and the inflation-adjusted discount rate (DR) was also varied. However, for consistency in comparing different strategies, results for an ICF of 2 and a DR of 3 percent are presented as the "base-line" results.

114. One aspect that will surface in all of the results presented in this chapter is the trade-off between the costs of replacement and of repair. As was shown in Figure 1, summing the two costs yields the total cost, allowing determination of the minimum cost strategy. However, the important aspect

when addressing these costs is the fact that, in general, the majority of replacement costs are incurred early in the simulation and repair costs arise in later years. This aspect is important for two reasons: (a) the two actions are linked; in general, large, early replacement costs will result in lower repair costs (and vice versa) (b) since costs are discounted, the present value of a $1 repair cost in year 2 is less than the present value of a $1 replacement cost at time zero. The degree to which this is true, of course, will depend on the selected discount rate.

Number-of-Breaks Strategies

115. A series of strategies, in which replacement was based on the number of breaks a pipe experienced over its lifetime (type 1 strategies), were tested to determine the best one. Five different strategies were analyzed: replace all pipes that have had x or more breaks (where x equals one, two, three, or four) and a "do-nothing" strategy. All five of these strategies, including the do-nothing case, removed 10 percent of 6-in. pipes each year, for the first 10 years of the simulation.

116. This section presents results of the application of type I strategies utilizing both sets of input costs (Tables 9 and 10). Although the input data in Table 10 are more realistic, results using both provide an interesting comparison and will be presented. In all cases no budget constraint was imposed. Imposition of the budget limitations (Table 11) increased the overall costs, but did not have a drastic effect. A more detailed examination of results with a budget limitation is presented in a later section.

117. Table 12 shows the present value of costs for all five type I strategies for the five boroughs and New York City as a whole. For this case indirect costs were designated as equal to 100 percent of direct repair costs (ICF = 2.0), the inflation-adjusted DR was 3 percent and Table 9 input costs were used (uniform replacement costs over all boroughs and repair costs varying with diameter of pipe). In Table 12 (as will be the case henceforth), the least-cost strategy for each borough is underlined. As can be seen from the results, the strategy of replacing all pipes with one or more breaks resulted in the lowest cost in all cases.

Table 12

Present Value of Costs (in millions of dollars) for

Type I (Number-of-Breaks) Strategies

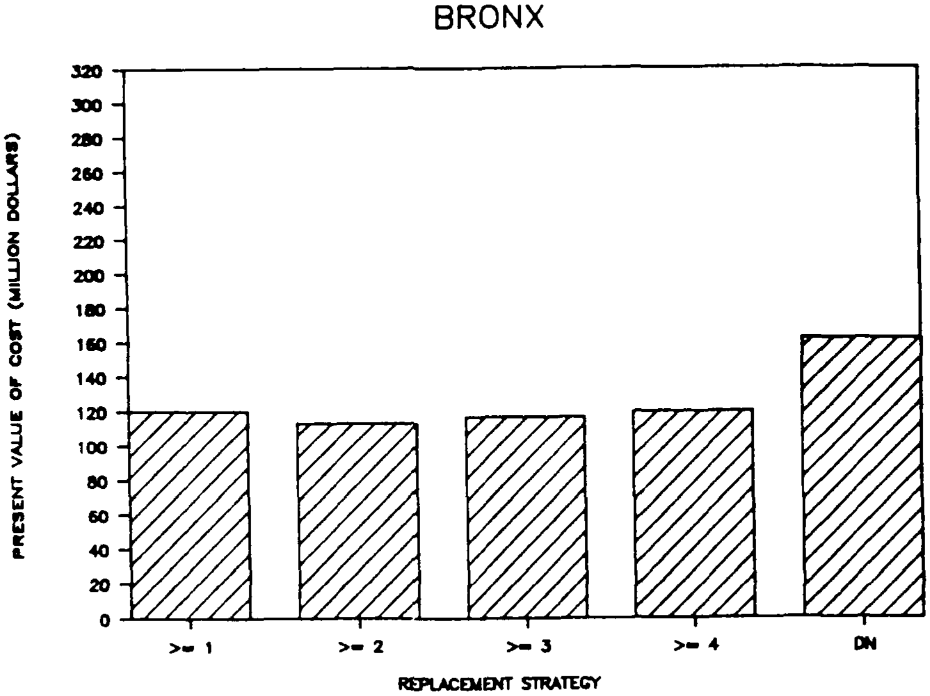
(ICF = 2.0, DR = 3%, Table 9 Input Costs)

Borough	Strategy ≥1	≥2	≥3	≥4	DN
Bronx	132.0	144.8	162.2	170.7	251.8
Brooklyn	265.5	272.7	288.0	295.4	353.5
Manhattan	206.9	234.6	287.6	322.1	757.7
Queens	158.7	166.7	178.0	182.9	215.4
Staten Isl.	46.6	50.9	54.5	55.8	63.2
NYC Total	809.7	869.7	970.3	1,026.9	1,641.6

118. Although the effect of changing the DR will be examined in a later section, it is interesting to note that when the DR is raised by 2 (to 5 percent), the two-or-more strategy is selected as the least-cost approach. In addition, for two of the boroughs, at DR = 5 percent the three-or-more strategy is best.

119. When different cost data are used, the results change dramatically. Table 13 shows the results using the cost data shown in Table 10. All other parameters are the same as for the results shown in Table 12. (ICF = 2, DR = 3 percent, no budget constraint). In addition, the results are shown in Figure 7. For this case, the least-cost strategy for New York City as a whole is to replace pipes that have had two or more breaks. If each borough is investigated separately, different least-cost strategies are observed. For example, in Brooklyn and Manhattan the three-or-more break strategy yields the least cost, in the Bronx and Queens the two-or-more strategy is best, while in Staten Island, the one-or-more break strategy yields the lowest final cost.

120. It might be expected that Manhattan, which has the highest overall break rate, would profit from a more aggressive strategy, relative to the other boroughs. This is not the case, however, because Manhattan has the second highest percentage of large mains (11.8 percent) and replacement costs for these mains are great. As a result, the less aggressive strategy yields a



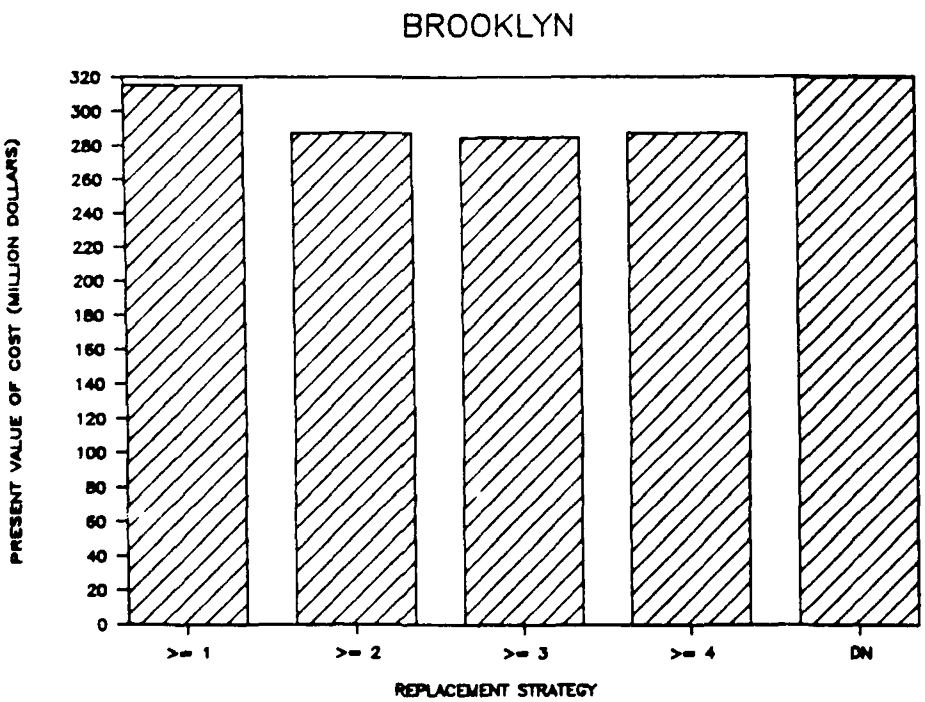


Figure 7. Present costs (in millions of dollars) for type I strategies (ICF = 2.0, DR = 3 percent, Table 10 input costs) (Sheet 1 of 3)

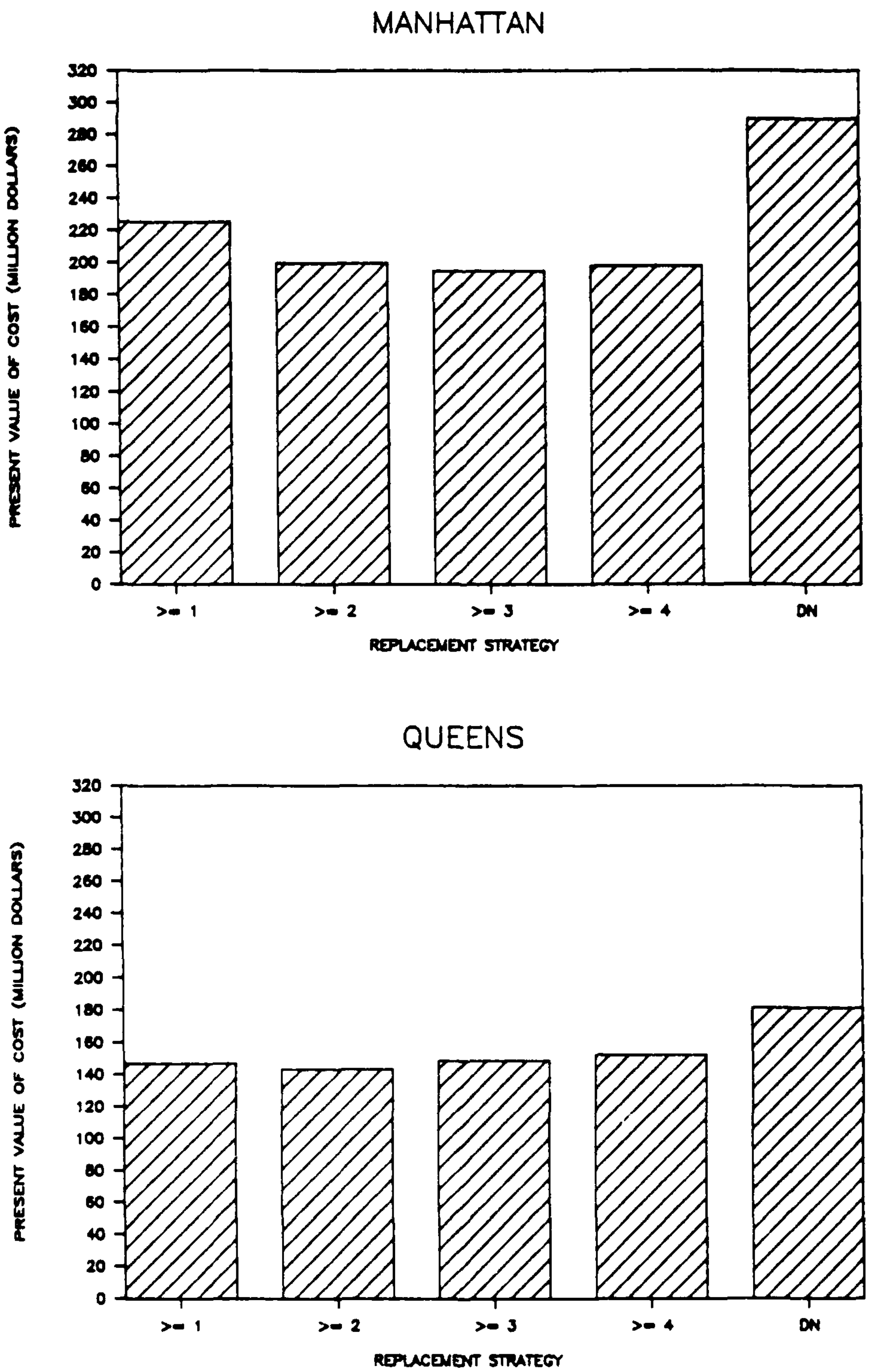


Figure 7. (Sheet 2 of 3)

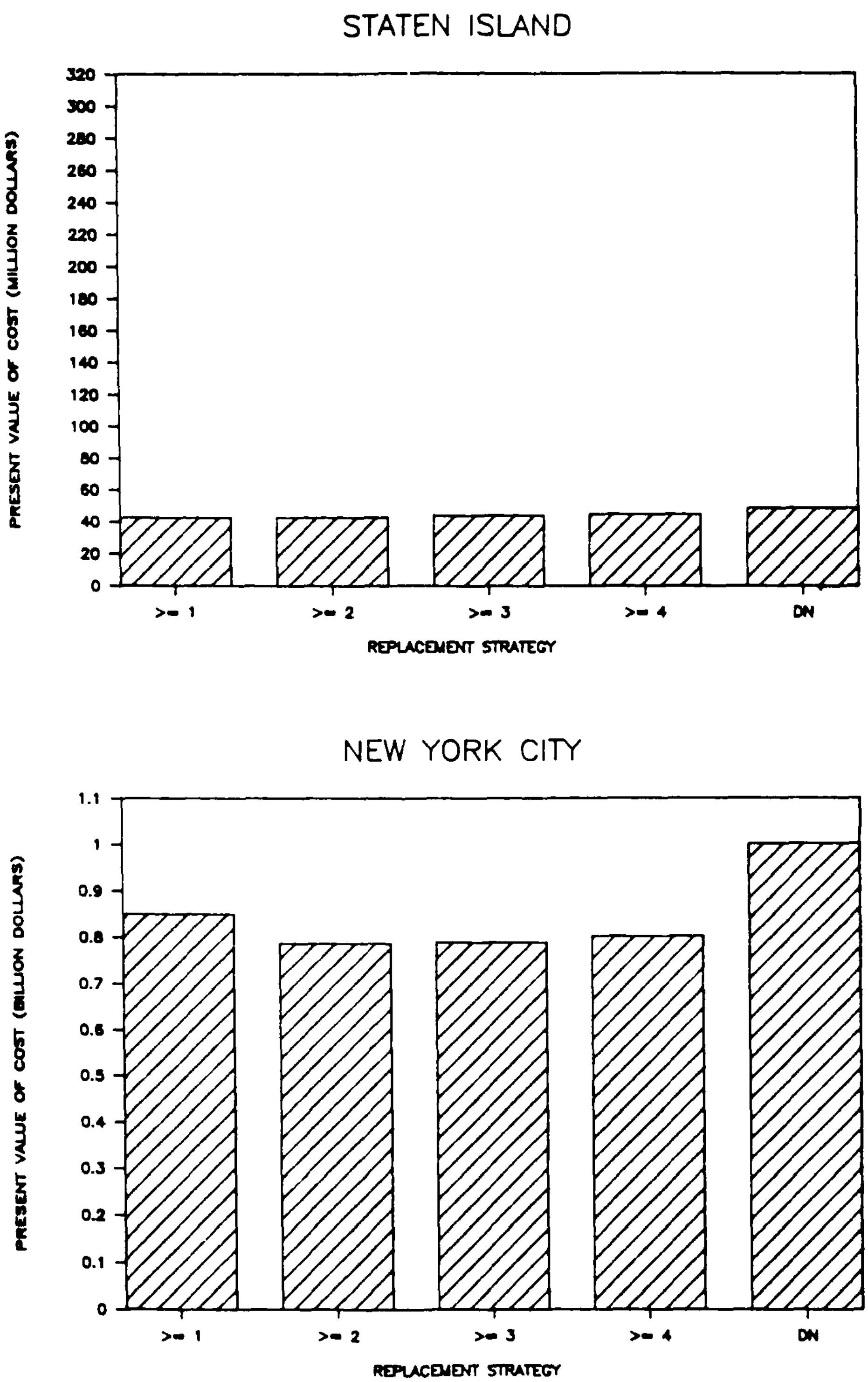


Figure 7. (Sheet 3 of 3)

Table 13

Present Value of Costs (in millions of dollars) for Type I (Number-of-Breaks) Strategies (ICF = 2.0, DR = 3 Percent, Table 10 input costs)

Borough	Strategy ≥1	≥2	≥3	≥4	DN
Bronx	120.2	113.3	116.8	120.1	162.2
Brooklyn	315.4	287.6	285.0	287.2	319.6
Manhattan	225.5	199.7	195.0	198.2	289.9
Queens	147.1	143.4	148.9	152.3	181.6
Staten Isl.	42.8	43.0	44.3	44.9	48.8
NYC Total	851.0	787.0	790.0	802.7	1,002.1

lower cost. This result is supported by results for application of different strategies to different diameters, which are presented in a later section. In addition, the replacement costs for aggressive strategies are larger than the repair costs because in the first year of the simulation there is a backlog of mains that must be replaced. Because the cost to replace mains is not discounted during the first year, the problem is doubly compounded: many mains are replaced and the present value of the cost of replacing these mains is high.

121. Another relevant observation is that in some cases the difference in cost between the least-cost strategy and the next-most-expensive strategy is very small. For example, for Manhattan, the cost of the second-best strategy is only \$4.7 million (about 2.5 percent) higher than the least-cost strategy. The values for Staten Island provide an even more concrete example. Disregarding the DN strategy, the other four strategies all have costs within \$2.1 million, or approximately 5 percent, of each other. For Staten Island, when addressing economic aspects only, one could conclude that application of any of the four type I strategies (given ICF = 2.0 and DR = 3 percent) would yield similar results.

122. Comparing the results shown in Tables 12 and 13 reveals that less aggressive strategies are better for input of the costs shown in Table 10. For two boroughs in particular, Brooklyn and Manhattan, the selected strategies are quite different. These results are logical though, when considering the fact that replacement costs for Brooklyn and Manhattan in the second case (Table 13) were higher than the first case (Table 12). The other factor that contributes to the difference in results is the variance in repair costs (for different diameters) between the two cases and the relative number of mains of different diameters for the various boroughs. Both of these aspects contribute to the selection of more passive strategies.

123. It is clear from Tables 12 and 13 that by applying different strategies to different boroughs, the cost to New York City can be decreased, but only by a small amount. In Table 12, all least-cost strategies are the same, resulting in no difference. In Table 13, to produce the least-cost approach, the two-or-more break strategy should be applied to the Bronx and Queens, a three-or-more break strategy should be applied to Brooklyn and Manhattan, and a one-or-more break strategy should be applied to Staten Island. This approach yields a cost of $779.7 million which is $7.3 million less than the $787.0 million resulting from application of one strategy (replacing pipes with two or more breaks) uniformly across all boroughs. In this case the borough-by-borough application of strategies yields slightly lower costs. The savings are not particularly large considering the fact that these values represent savings over all 50 years of the simulation.

124. The relationship of repair and replacement costs for various strategies provides interesting insight. As would be expected, replacement costs are higher for more aggressive strategies, while repair costs are higher for passive strategies. Figure 8 shows the breakdown of repair and replacement costs for five strategies. The plot represents one case (discount rate = 3 percent and ICF = 20) for Brooklyn, and is fairly representative of other boroughs, although in several cases the total cost curve is not as flat.

Percentage Strategy

125. Results for a different type of strategy (type II) were also examined; that of replacing a set percentage of main segments each year. As in the previous section, 10 percent of the 6-in. mains were removed each year

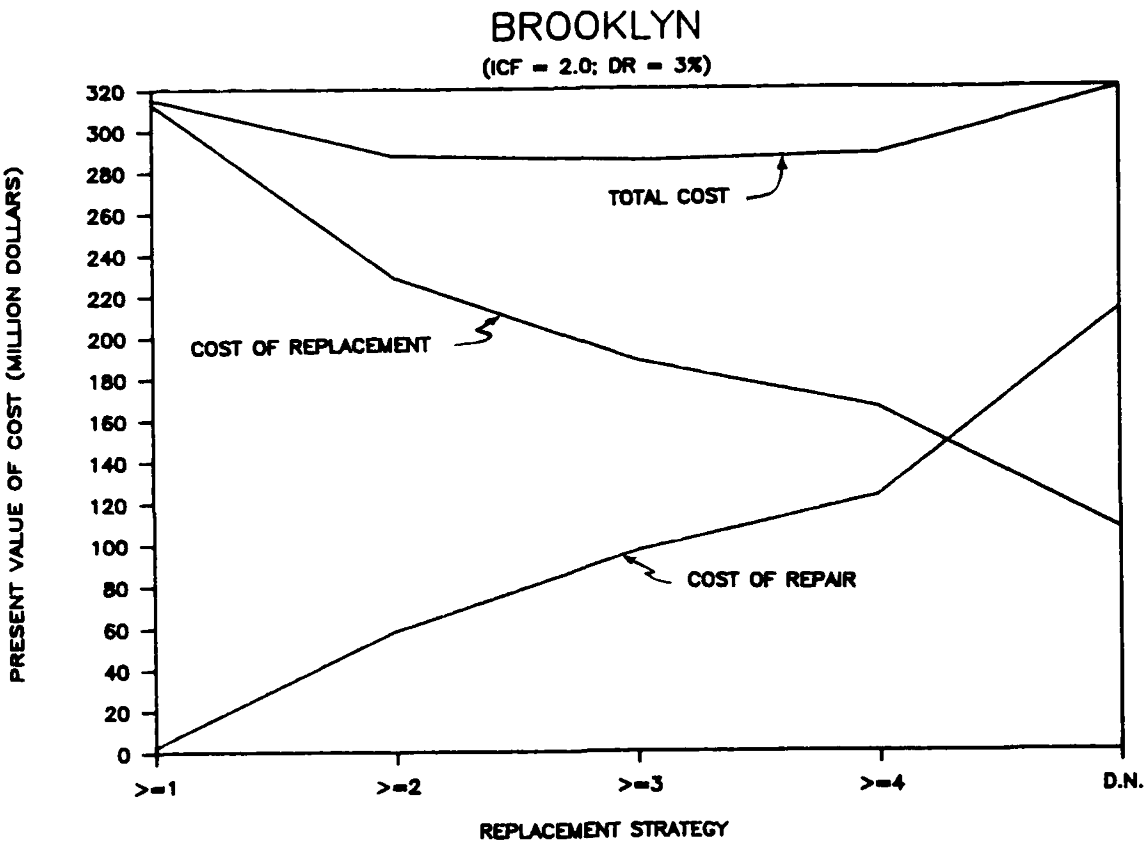


Figure 8. Repair, replacement, and total cost for type I strategies for Brooklyn (ICF = 2.0, DR = 3 percent, Table 10 input costs)

(for the first 10 years). The reader should also remember that the percentage removal strategy does not randomly replace pipes, but selects those with the worst break records. For all simulations, an ICF of 2.0 and a DR of 3 percent were assumed. The results of this analysis are shown in Table 14 with the lowest costs for each borough underlined. In addition, the results are shown in Figure 9. The results reveal that a more aggressive strategy should be applied to Manhattan, with progressively less aggressive strategies applied to the Bronx, Brooklyn, Queens, and Staten Island, respectively. In general, more aggressive strategies result for those boroughs with higher break rates. This general pattern contradicts the results that were obtained in the previous section (for the type I study). This phenomenon will be discussed later in the section.

126. For the city as a whole, the results in Table 14 indicate that replacing 0.25 percent of the system each year (or about 14 miles per year) results in the least cost. Since New York City currently replaces about

Table 14

Present Value of Costs (in millions of dollars) for Type II (Percentage) Strategies

(ICF = 2, DR = 3 Percent, Table 10 Input Costs)

	Percentage of Mains Removed							
Borough	2.0	1.0	0.50	0.40	0.25	0.10	0.050	0.0(DN)
Bronx	244.7	161.7	140.7	141.1	143.7	151.8	156.4	162.2
Brooklyn	693.8	434.0	329.4	316.1	304.5	306.7	312.0	319.7
Manhattan	280.9	251.8	262.2	266.8	274.7	283.5	286.7	289.9
Queens	398.8	235.9	172.3	163.4	158.4	165.3	172.3	181.6
Staten Isl.	200.4	109.1	67.0	59.5	50.2	45.7	46.1	48.8
NYC Total	1,818.6	1,192.5	971.6	946.9	931.5	953.0	973.5	1,002.2

0.5 percent of its system each year*, this result (for ICF = 2.0 and DR = 3 percent) suggests that more pipes are being replaced each year than might be necessary. This result, however, cannot be easily generalized, particularly since past replacement has included a large number of 6-in. mains. Different values for DR and ICF would easily shift the results. In addition, other aspects beyond the scope of this report must be considered in the real world. These include, for example, replacement of mains to improve carrying capacity and opportunistic replacement before street repaving.

127. The use of the simulation model to assess both type I and type II strategies revealed several interesting results. The first is that type I strategies, particularly the more aggressive ones, replace a very large number of mains during the first year of simulation since there is often a large backlog of mains that need to be replaced. This result is not true for the type II strategies. By the very nature of type II strategies, an equal portion of mains are replaced each year. This basic difference in the approaches

* Comments by the City of New York on a draft of this report indicated that the replacement percentage is closer to 1 percent if 6-in. mains are included. If 6-in. mains are excluded 0.5 percent is correct.

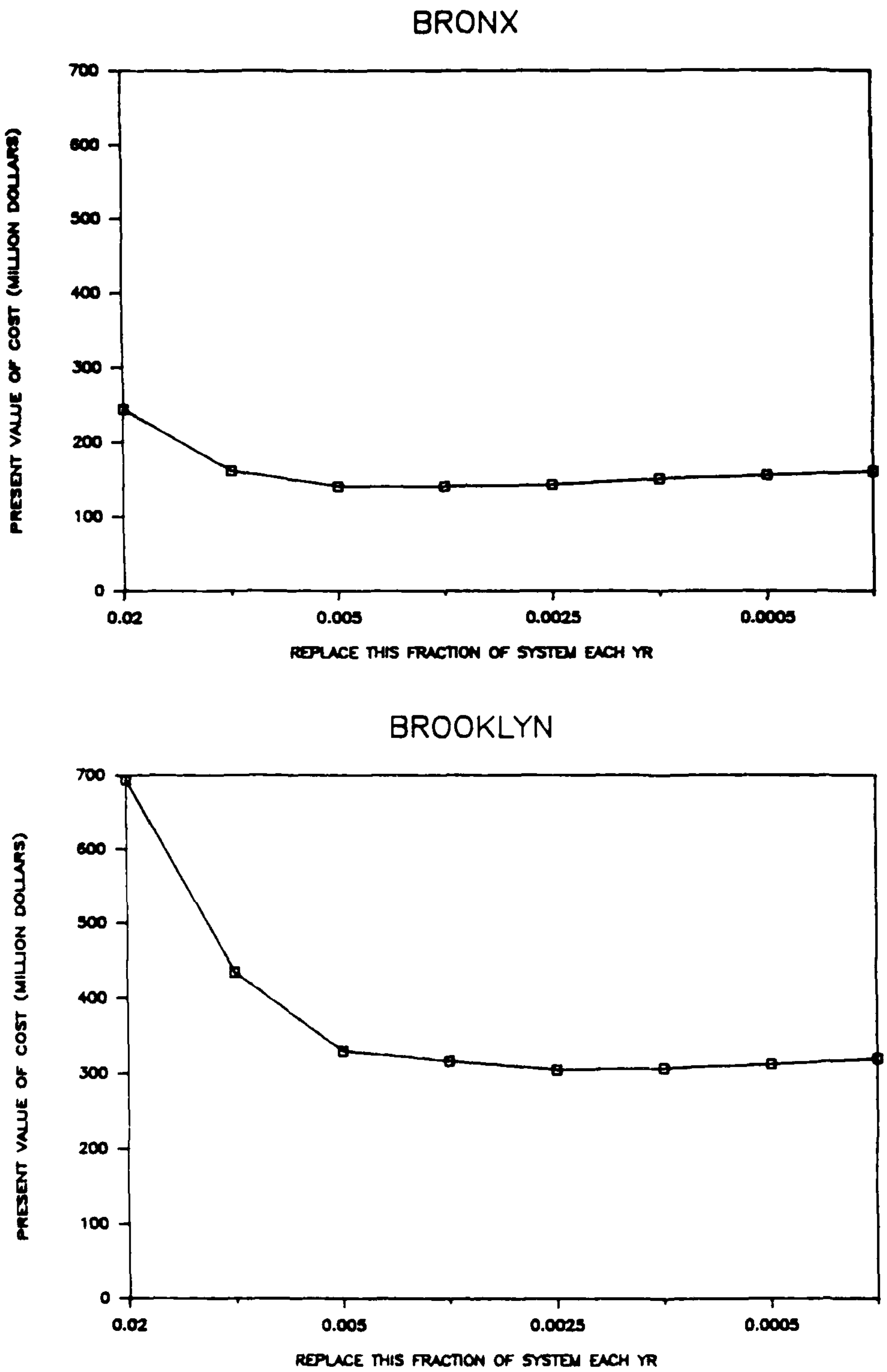
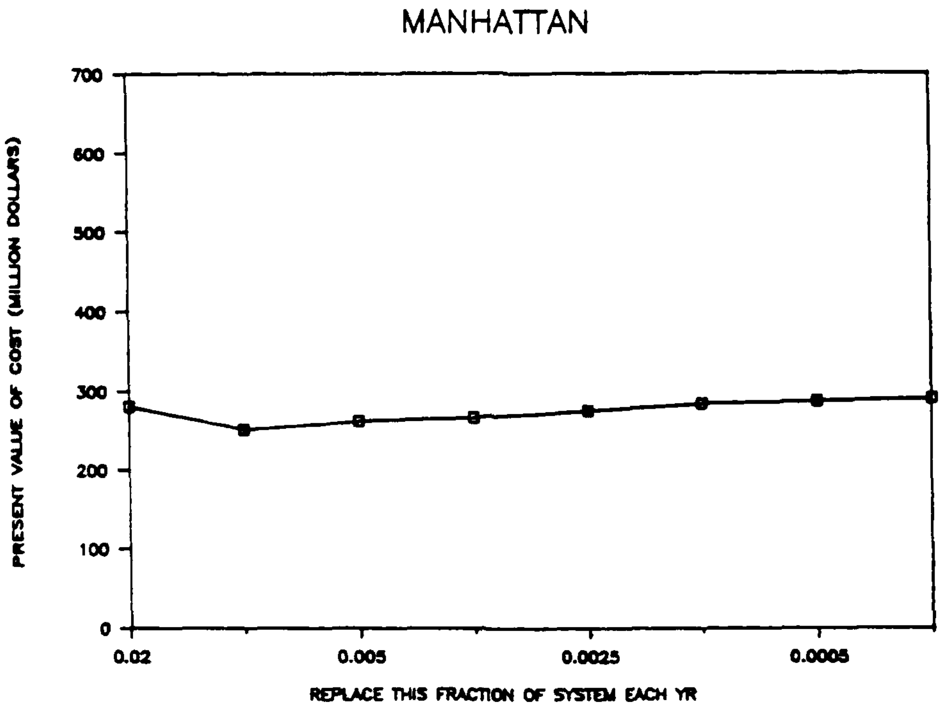


Figure 9. Present cost (millions of dollars) for Type II strategies (ICF = 2.0, DR = 3.0 percent, Table 10 input costs) (Sheet 1 of 3)



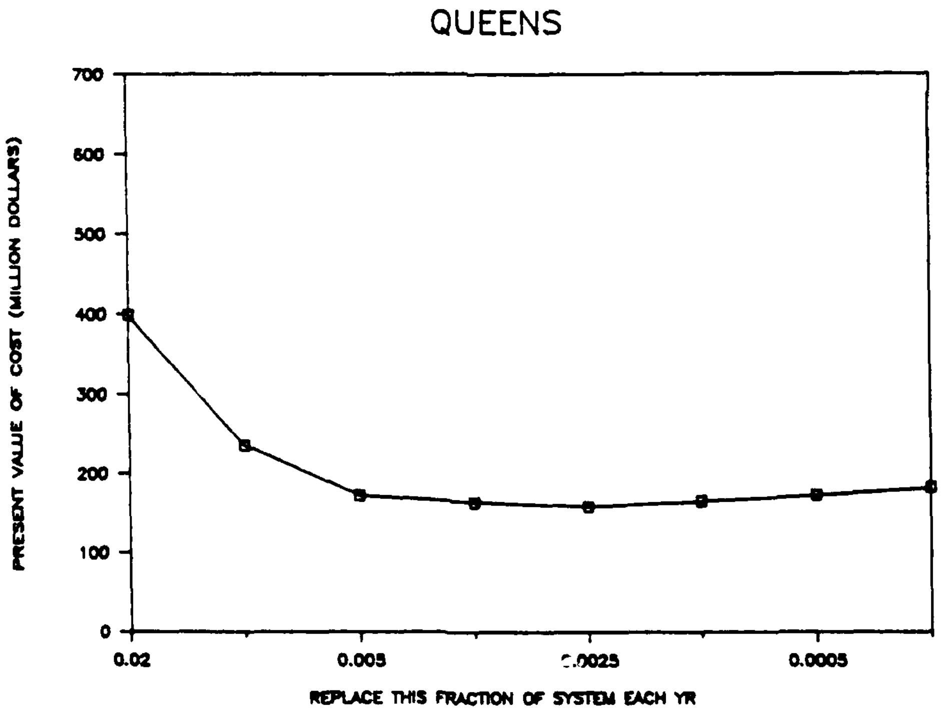
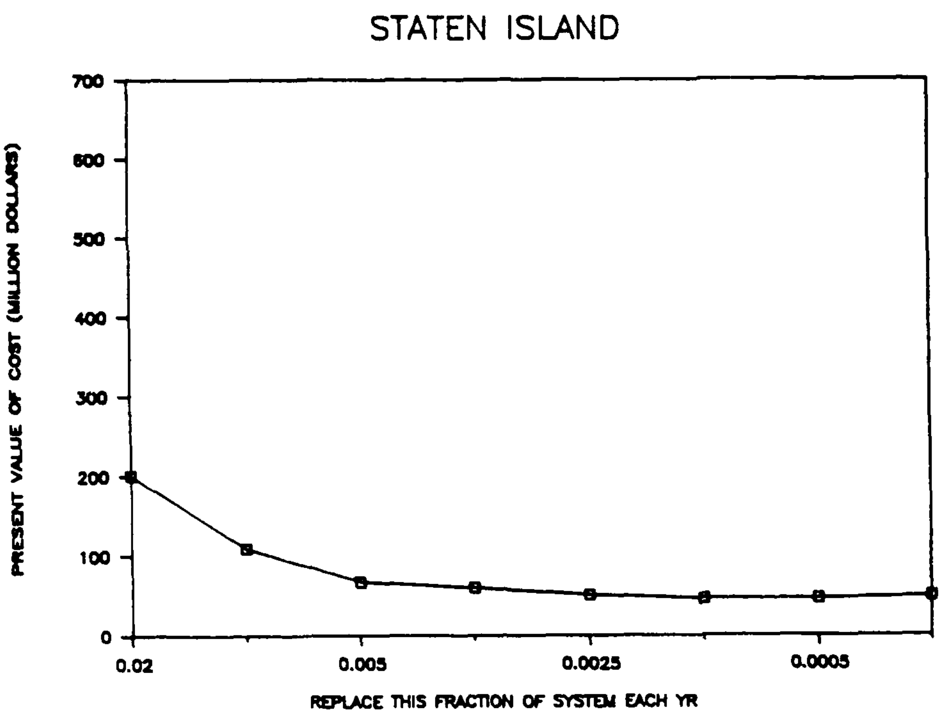


Figure 9. (Sheet 2 of 3)



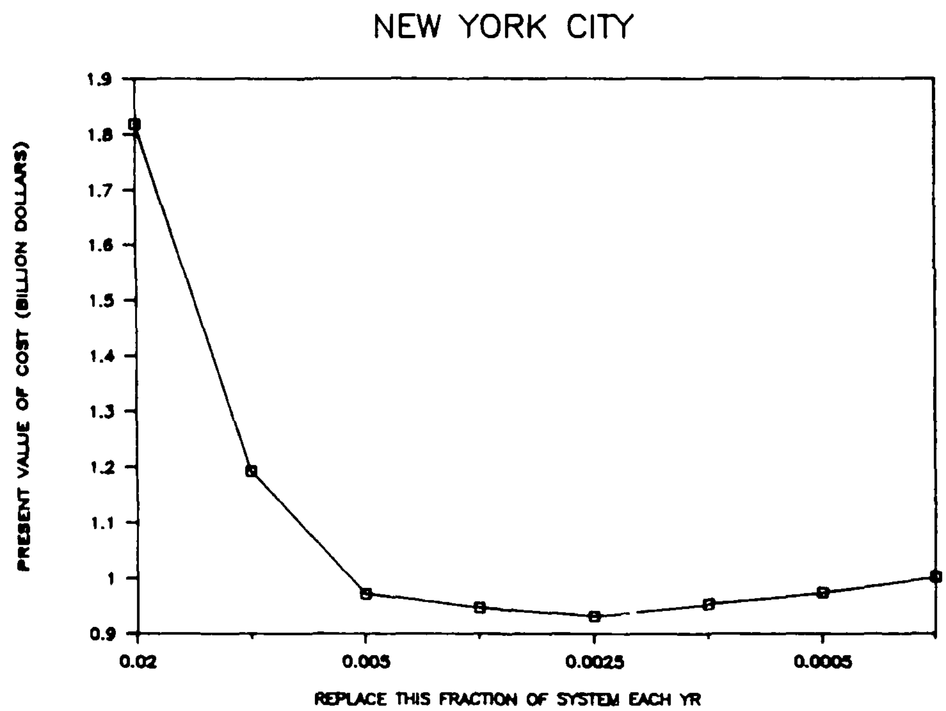


Figure 9. (Sheet 3 of 3)

of the type I and type II strategies yields interesting differences in their results.

128. The reader will notice that the least-cost type I strategies have lower costs than the least-cost type II strategies. For example, for an ICF of 2.0 and a DR of 3 percent, the cost for the optimal type II strategy for the entire city increased by $144.5 million, or about 18 percent over the type I approach. On average, the percentage increase for the individual boroughs was about 15 percent. This is a result of the fact that application of type I strategies results in many mains being replaced during the first year of the simulation, while the type II strategies do not replace this backlog of mains in the first year. As a result, for the type II strategies, many ailing mains are left in the ground to break. These breaks eventually become excessive and result in fairly high repair costs which, in turn, contribute to the present-value total cost. The conclusion is that early attention should be placed on those pipes that represent the backlog (i.e., existing pipes that are in poor condition).

129. Another interesting difference between the results of the type I and type II strategies is the difference in least-cost strategies selected for the five boroughs. In general, application of type I strategies resulted in less aggressive strategies being selected for Brooklyn and Manhattan. The opposite was true for type II strategies. Again, the reason is the large number of mains being replaced during the first year. For example, in Manhattan, (ICF = 2.0 and DR = 3 percent) the least-cost type I strategy replaced 7.6 percent of the system during the first year. The least-cost type II strategy replaces only 1 percent of the system. Therefore, the fairly passive type I strategy of replacing pipes with four or more breaks is actually much more aggressive (during the first year in particular) than the aggressive type II strategy of replacing 1 percent of the system each year. Clearly, the percentage that is removed each year in the type I approach decreases each year, particularly after year 10 when all 6-in. mains have been replaced.

130. The impact of the first year removal on the selection of type I strategies can be emphasized by addressing the results of the simulations without adding in the cost of the first year's actions. In other words, the simulation was applied to the boroughs as if the first year (of replacement and repair) had already taken place. The results are far less costly because the large replacement during the first year was not included. In addition to

the reduction in costs, more aggressive least-cost strategies are selected. The effect of the first year raises the question of whether two strategies should not be considered: (a) a short-term strategy, intended to deal with the backlog of ailing pipes, and (b) a long-range strategy, intended to maintain the balance between replacement and repair.*

131. The basic difference in the type I and type II strategies makes comparison of their results difficult. There are five discrete type I strategies while an infinite number of type II strategies are possible. In addition, the type I approach determines the number of mains to replace based on the condition of the system. As a result, a large number are replaced in the first year, particularly for aggressive strategies. Type II strategies replace a set number of mains each year (based on the selected percentage) regardless of the condition of the system.

Replacement Based on Diameter

132. Pipes with different diameters, like different boroughs, have different break rates associated with them. In addition, replacement costs (Table 10) are quite different. Therefore, different strategies might also be best applied to each diameter group to produce a least-cost strategy. To test this hypothesis, the type I strategies were applied to each diameter group (along with 10 percent removal of the 6-in. mains each year, for the first 10 years). For example, the one-, two-, three-, four-or-more, and do-nothing strategies were tested on the 8-, 12-, and 16- to 24-in. diam groups. Table 15 shows the results for the five boroughs for the case where ICF = 2.0 and DR = 3 percent. If different type I strategies are applied to different diameter pipes in the Bronx, for example, applying a two-or-more-break strategy to 8- and 12-in. diam pipes and a three-or-more-break strategy to 16- to 24-in. diam pipes would yield the lowest cost, $113 million. In all cases, the least-cost strategies are those that apply an aggressive strategy to the smaller mains and a more passive strategy to the larger mains. There are two reasons for this phenomenon: (a) smaller mains are known to have higher break

---

* Comments by the City of New York on a draft of this report indicated their current policy calls for replacing mains with two breaks, 6-in. mains, and mains involved in the joint highway-sewer program.

Table 15

Least Cost Type I Strategy Applied to Different Diameter Groups and Associated Cost of the Strategy (ICF = 2.0, Dk = 3 Percent, Table 10 Input Costs)

Borough	Pipe Diameter, in. 8"	12"	16-24"	Cost ($million)
Bronx	≥2	≥2	≥3	113
Brooklyn	≥2	≥3	DN	283
Manhattan	≥2	≥3	≥4	195
Queens	≥2	≥2	≥4	143
Staten Isl.	≥1	≥2	≥4	42

rates and are, therefore, usually good candidates for replacement, and (b) larger mains cost more to replace. It should be remembered, however, that these results are based on replacement costs that increase with diameter and repair costs that are the same across all diameters. Using different break cost data (e.g. Table 9) might yield different results.

133. As is shown in Table 16, the final costs of applying strategies to diameter groups in a nonuniform manner were reduced somewhat over strategies applied uniformly across all diameters. For example, in Brooklyn the lowest cost is reduced from $285 million to $283 million. This result is expected because the strategy could come closer to an optimal strategy by applying a different strategy to each diameter group. However, cost reductions are almost insignificant, particularly when considering the fact that the costs represent present values that were discounted on a 50-year period.

134. The average percent reduction achieved with the nonuniform strategy over all five boroughs was 0.56 percent. Staten Island is the only borough to show a "measurable" change in costs, decreasing by 2.1 percent. This larger percentage decrease, however, is mostly a result of the fact that the total cost for Staten Island is much less than the other boroughs. These results demonstrate that, when applied to planning studies, the additional complexity involved in addressing different diameter pipes with different strategies is probably not worth the effort. However, when addressing actual

Table 16

Comparison of the Present Cost for Least Cost Type I Strategies Applied Uniformly to all Diameters and Applied Separately Over Different Diameters*

Borough	Uniform Strategy	Non-Uniform Strategy	Decrease	% Decrease
Bronx	113**	113	0	0
Brooklyn	285	283	2	0.7
Manhattan	195	195	0	0
Queens	143	143	0	0
Staten Isl.	42.8	41.9	0.9	2.1

* ICF = 2.0, DR = 3 percent, Table 10 input costs.
** All values are given in millions of dollars.

year-to-year maintenance/replacement decisions, the distinction may be more realistic. In such cases more aggressive strategies should be applied to smaller diameter pipes.

Replacement Based on Period Installed

135. Because pipes laid in different age groups have different characteristics, application of different strategies to these different groups could reduce the total cost over uniformly applying the same strategy to all age groups. A combination of type I and type II strategies was used to accomplish this task. Two type I strategies (≥1 and ≥2) were applied to all age groups; however, only designated portions of all mains that normally would have been replaced were actually replaced. For example, for the two-or-more strategy, rather than replacing all mains that had incurred two or more breaks, only a percentage of those mains (those with the most breaks) were replaced. For this study 50 percent of the mains in the post-1930 age groups were replaced and three different percentages (50, 75, and 100 percent) were applied to the pre-1930 age groups. In this way, more aggressive strategies were applied to the oldest age group relative to those applied to newer age groups.

136. As can be seen in Tables 17 and 18, removal of a larger portion of mains in the old age group does not yield significant savings. Only the costs

Table 17

Present Cost of Strategy Which Replaces 50% of All Mains with Two or More Breaks for Post-1930 Age Groups and Designated Percentage of All Mains with Two or More Breaks for Pre-1930 Age Groups*

Borough	Percent Removed From Pre-1930 Age Groups		
	50%	75%	100%
Bronx	112.7**	112.8	112.9
Brooklyn	277.3	282.5	285.4
Manhattan	210.4	205.2	202.7
Queens	141.8	142.8	143.4
Staten Isl.	41.9	42.2	42.8
NYC Total	776.7	781.1	783.5

* ICF = 2.0, DR = 3 percent, Table 10 input data.
** All values are given in millions of dollars.

Table 18

Present Cost of Strategy Which Replaces 50% of All Mains with One or More Breaks for Post-1930 Age Groups and Designated Percentage of All Mains with Two or More Breaks for Pre-1930 Age Groups*

Borough	Percent Removed From Pre-1930 Age Groups		
	50%	75%	100%
Bronx	119.4**	119.6	119.7
Brooklyn	305.3	310.1	313.1
Manhattan	227.7	226.0	225.1
Queens	145.5	146.3	147.0
Staten Isl.	41.6	41.8	42.1
NYC Total	839.5	843.8	847.0

* ICF = 2.0, DR = 3 percent, Table 10 input data.
** All values are given in millions of dollars.

for Manhattan are decreased as a result of applying a more aggressive strategy to the older mains. For Manhattan the decreases were 3.7 and 1.1 percent over applying a uniform policy for all age groups. The results for Manhattan (when compared to the other boroughs) are logical since Manhattan has a larger portion of older mains, many of which are smaller in diameter.

137. The results also reveal an interesting phenomenon about application of type I strategies in general. Comparisons were made earlier between different type I strategies. For example, Table 13 shows the costs for ≥2 and ≥3 strategies for the Bronx. However, for the Bronx, Table 16 shows a least-cost strategy of removing only 50 percent of mains with two or more breaks. The cost of $112.7 million is slightly less than the $113.3 million value that was best in Table 13. This result indicates that, for the Bronx, a strategy somewhere between the ≥2 and ≥3 strategies is slightly better.

Effects of ICF and DR

138. The results of the simulations are sensitive to both the ICF and the DR. Values of 2.0 and 3.0 percent were used for the ICF and DR, respectively. However, neither value is known with certainty. In this section sensitivity analyses are presented by showing the results for ICF values of 1.0, 2.0, 3.0, and 4.0 and DR values of 1.0, 3.0, 5.0, and 7.0 percent.

139. Increasing the value of the ICF will always increase the total cost, since a higher factor means that a higher total cost is assigned to repairing a break. However, use of different cost factors might also result in selection of different least-cost strategies. Table 19 illustrates this fact using results for Brooklyn. (Results using a discount rate of 5.0 percent are shown since they illustrate the trend better.) Figure 10 also displays the trend, showing that more aggressive strategies take over as the least-cost choice as the ICF value increases. This general trend is typical of other boroughs and for other DR's. The results are logical since the ICF adds to the cost of repair and not to the cost of replacement. As the cost of break repair increases relative to the cost of replacement, a more aggressive strategy (which will result in fewer breaks) is selected.

140. The discount rate has a significant effect on the total cost and on the selection of the least-cost strategy. Since future costs are discounted, their present value will decrease with an increasing DR. In general,

Table 19

Present Cost (in millions of dollars) of Type I Strategies for Brooklyn*

ICF	Strategy ≥1	≥2	≥3	≥4	DN
1.0	298.4	212.9	185.4	174.3	161.8
2.0	299.6	234.3	219.5	216.7	227.2
3.0	300.8	255.7	253.7	259.0	292.7
4.0	302.1	277.1	287.9	301.3	358.1

* DR = 5 percent, Table 10 input costs.

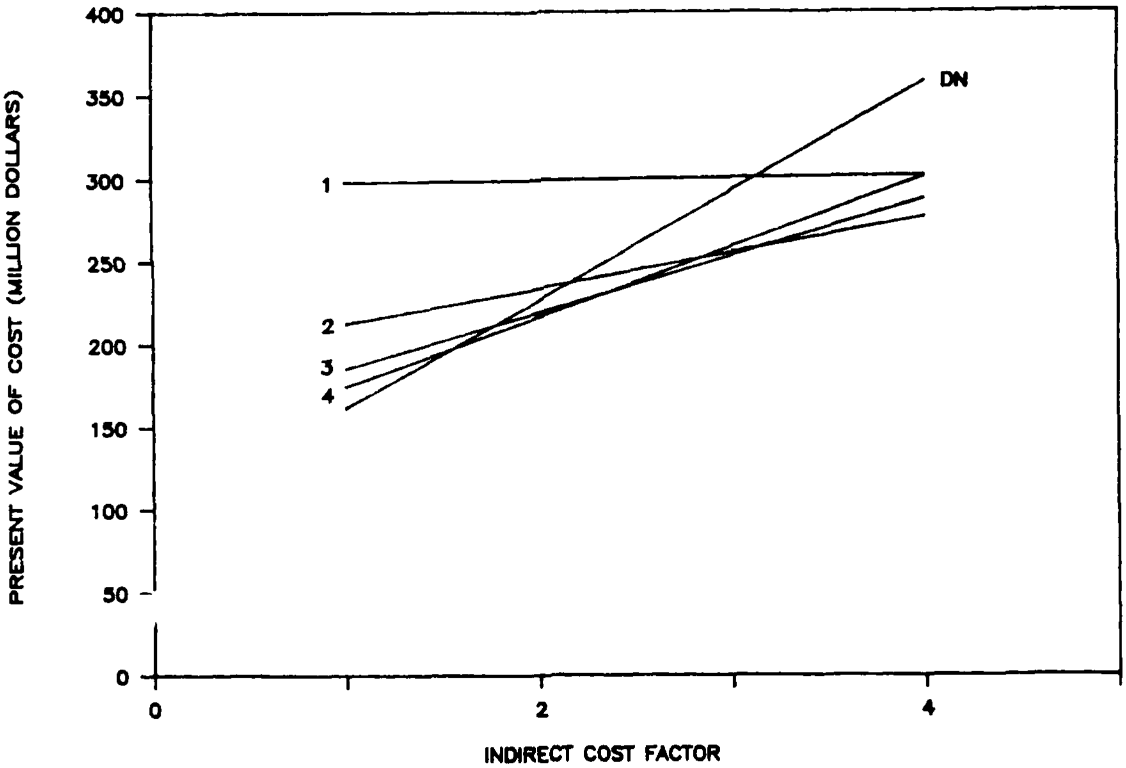


Figure 10. Present cost of five strategies with ICF's for Brooklyn (DR = 5 percent, Table 10 input costs)

repair costs constitute a larger fraction of future total costs. Therefore, a higher DR will tend to favor less aggressive strategies (those that allow more breaks). Table 20 illustrates the effect for all five boroughs and New York City as a whole, using an ICF factor of 2.0 and DR's of 1, 3, 5, and 7 percent. The selected strategies range from ≥1 to ≥4, but in no case was a do-nothing strategy chosen.

141. For all five boroughs and the city as a whole, raising or lowering the DR by 2 percentage points from the chosen rate of 3 percent will result in the selection of a more passive least-cost strategy (with one exception - Staten Island). This result is illustrated in Figure 11 for the entire city, where more passive least-cost strategies are selected as the DR is increased. Table 21 presents the results in a different way, showing, for the specified DR and for a selected strategy, the percent deviation of the cost for the selected strategy above that of the optimal strategy. In other words if a strategy of repairing three or more breaks were selected, for a DR of 3 percent, the cost would be only 0.4 percent above the least-cost strategy (≥2). In addition, if the three-or-more-break strategy were selected, the maximum deviation (for the range of DR's shown) would be 25.2 percent above a least-cost solution. Using this approach, it is possible to select, under uncertain circumstances, (i.e. unknown DR), a strategy that is close to the least-cost strategy. In this case either the ≥2 or ≥3 strategy is desirable.

142. The sensitivity analyses presented in the previous paragraphs point out the tenuous state of making firm decisions based on uncertain parameter values. However, the analyses also point out that, although the optimal choice may change with different input values, a good solution can often be obtained for a range of input values. Given an ICF of 2.0, replacing pipes with two or more breaks (or possibly three or more breaks) would be a good strategy to adopt. The result may not always yield the lowest cost; however, given uncertainties in the economic climate, it is likely to be close to optimal. If the ICF were slightly higher than 2.0, the two-or-more strategy would have a clear advantage over the three-or-more case.

143. The previous paragraphs concentrated on sensitivity analyses where strategies were uniformly applied to all pipe diameters. Similar results were obtained for sensitivity analyses when different strategies were applied to different diameters of pipe. The trends for these sensitivity analyses are shown in Figures 12 and 13. Figure 12 illustrates the case for Brooklyn,

Table 20

Present Cost for Type I Strategies*

Discount Rate	Strategy ≥1	≥2	≥3	≥4	DN
Bronx:					
1.0	124.8**	149.4	167.5	183.0	274.3
3.0	120.2	113.3	116.8	120.1	162.2
5.0	116.1	91.8	87.7	88.6	105.8
7.0	112.4	77.9	69.8	68.3	75.3
Brooklyn:					
1.0	332.0	375.6	398.1	415.5	497.8
3.0	315.4	287.6	285.0	287.2	319.7
5.0	299.6	234.3	219.5	216.7	227.2
7.0	288.2	199.2	178.5	173.0	175.0
Manhattan:					
1.0	233.1	241.0	258.0	279.0	491.2
3.0	225.2	199.7	195.0	199.4	289.9
5.0	218.1	173.5	156.6	152.4	188.8
7.0	211.7	155.5	131.5	122.7	134.2
Queens:					
1.0	153.4	197.6	221.2	238.1	301.7
3.0	147.1	143.4	148.9	152.3	181.6
5.0	141.5	111.9	108.7	109.9	120.9
7.0	136.6	92.1	84.5	83.5	87.7
Staten Island:					
1.0	45.0	61.2	67.3	70.6	79.3
3.0	42.8	43.0	44.3	44.9	48.8
5.0	41.0	32.6	31.8	32.0	33.3
7.0	39.4	26.3	24.5	24.3	24.7
NYC					
1.0	888.3	1,024.8	1,112.1	1,186.2	1,644.3
3.0	851.0	787.0	790.0	802.7	1,002.1
5.0	816.3	644.1	604.3	599.6	676.0
7.0	788.3	551.0	488.8	471.8	496.9

* ICF = 2.0, Table 10 input costs.
** All values are given in millions of dollars.

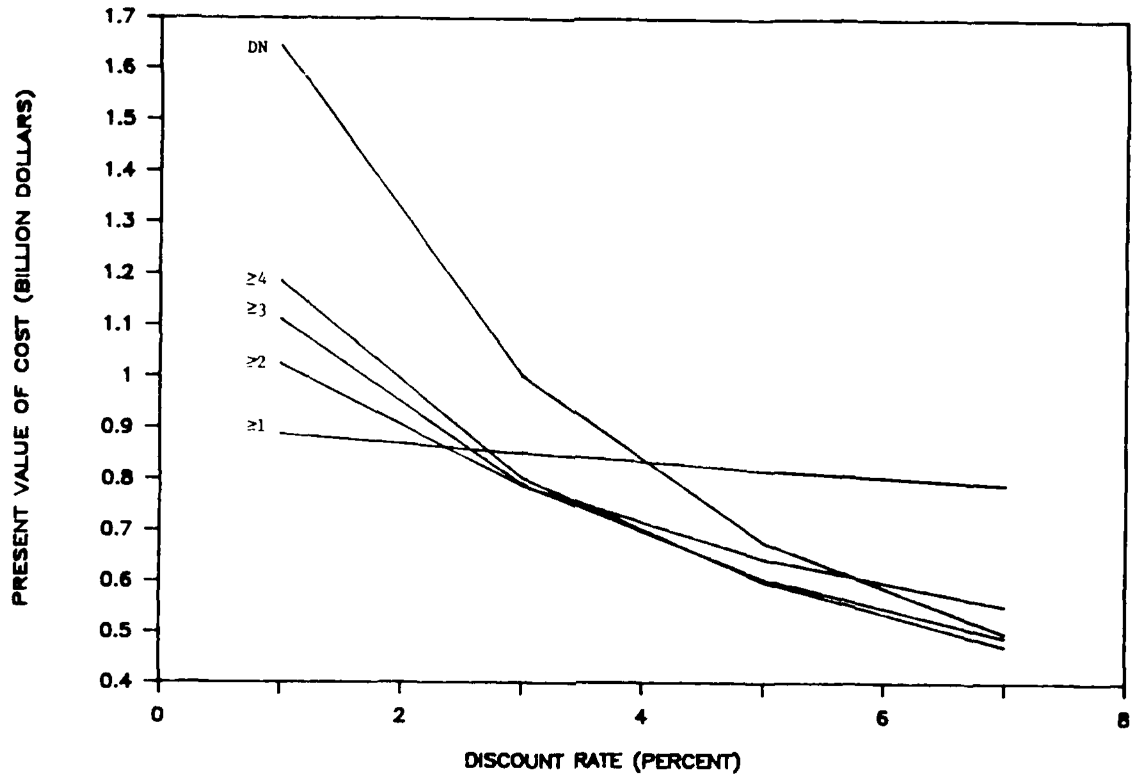


Figure 11. Present cost for New York City for five different strategies (ICF = 2.0, Table 10 input costs)

Table 21

Percent Deviation of Cost for Selected Strategy Above Least-Cost Strategy for Designated DR for New York City*

DR,%	Selected Strategy ≥1	≥2	≥3	≥4	DN
1	0	15.4	25.2	33.5	85.1
3	8.1	0	0.4	2.0	27.3
5	36.1	7.4	0.8	0	12.7
7	67.1	16.8	3.6	0	5.3
Maximum % deviation	67.1	16.8	25.2	33.5	85.1
Average % deviation	27.8	9.9	7.5	8.9	32.6

* ICF = 2.0, Table 10 input costs.

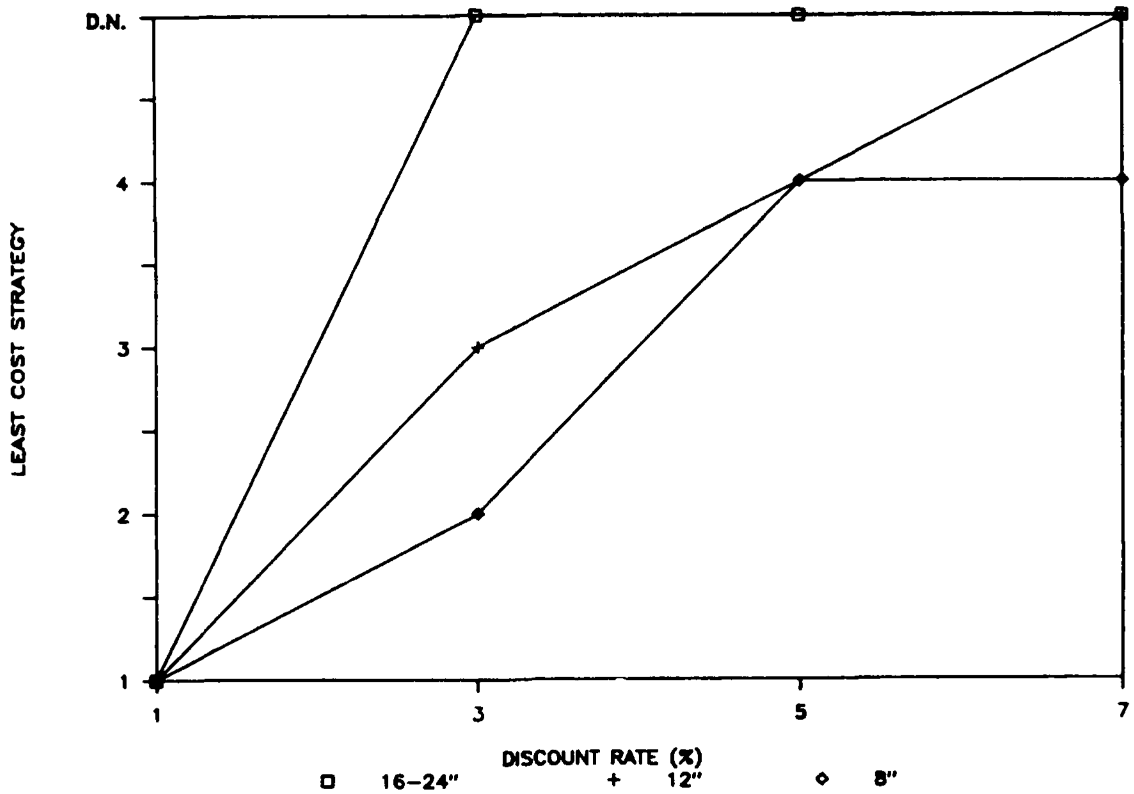


Figure 12. Type I strategies selected for different diameter groups for Brooklyn for different DR's (ICF = 2.0, Table 10 input costs)

where the least-cost strategies for the 8-, 12-, and 16- to 24-in. mains are shown for an ICF of 2.0 and DR's of 1, 3, 5, and 7 percent. Figure 13 illustrates the trend for ICF values of 2.0, 3.0 and 4.0, showing the selected strategies for Brooklyn for the 8-, 12-, and 16- to 24-in. mains for a DR of 5 percent. In almost all of these sensitivity analyses, even though the selection of strategies changed for different values of ICF and DR, for any selected ICF/DR combination, more aggressive strategies were always selected for small diameter pipe and less aggressive strategies for larger diameter pipe.

Effect of Budget

144. Application of the annual budget limitation (Table 11) to type I strategies did not have a drastic effect on the total cost, but did affect the selection of the least-cost strategy. Table 22 shows the results of the application of type I strategies (ICF = 2.0, DR = 3 percent, Table 10 input

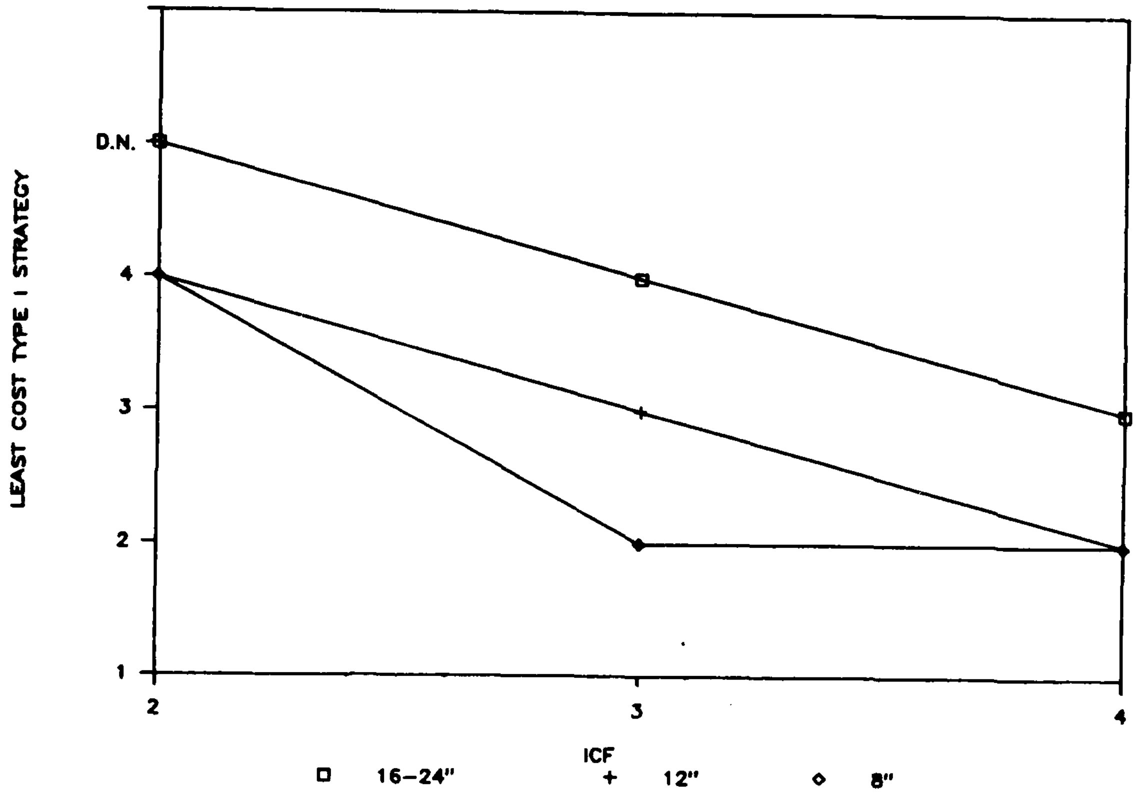


Figure 13. Type I strategies selected for different diameter groups for Brooklyn for different ICF's (DR = 5 percent, Table 10 input costs)

Table 22

Present Cost (in millions of dollars) for Type I (Number-of-Breaks) Strategies With a Budgetary Constraint*

	Strategy				
Borough	≥1	≥2	≥3	≥4	Do Nothing
Bronx	121.9	113.4	116.8	120.1	162.2
Brooklyn	303.5	285.6	285.0	287.2	319.6
Manhattan	232.0	213.1	201.3	199.9	289.9
Queens	149.5	143.4	148.9	152.3	181.6
Staten Isl.	43.0	43.0	44.3	44.9	[illegible]8.8
NYC Total	849.9	798.2	796.3	804.4	1,002.1

* ICF = 2.0, DR = 3 percent, Table 10 input costs.

costs). Application of the budget constraint results in the selection of a more passive least-cost strategy. Since this constraint applies only to those mains that are replaced, the effect is to constrain the degree of replacement but not repair, which is, in effect, a passive approach. Therefore, this result is not surprising since the budget constraint makes the more passive strategies more appealing, economically.

145. If the budget constraint curtails replacement in any year, it will usually increase the cost of a strategy. This can be seen by looking at Manhattan in Tables 13 and 22. Application of the least-cost strategy without the budget constraint results in a cost of $195 million. When the budget constraint is applied, the lowest cost increases to $199.9 million. This scenario is to be expected since the strategy changes when the constraint is applied. The three-or-more break strategy, which produced the lowest final cost without the budget constraint, is no longer the optimal strategy with the budget constraint. Instead, the simulation selects a four-or-more break strategy.

146. Table 23 compares the results of the simulation with and without the budget limitation. The budget constraint did not affect the results for the Bronx, Brooklyn, and Queens because the annual amount was sufficient to replace all mains that required replacement for the designated strategy. The effect of the budget is most obvious for Manhattan where, with the institution of the budget constraint, a more passive strategy is called for, resulting in a cost increase. This result must be addressed in light of the determination of the individual borough budgets. These budgets were determined by apportioning the total budget for NYC ($60 million)* by the length of main in each borough. Manhattan has a relatively small number of mains, yet a much larger problem in terms of breakage. A different allocation of funds might have changed the results.

147. In many of the cases, the budget constraint affects replacement during the first year of the simulation only. This statement is true particularly with aggressive strategies where a large backlog of mains were to be replaced during the first year. It is likely that application of progressively more restrictive budgets would result in solutions that more closely

---

* A more recent 10-year plan calls for a budget of $1.329 billion ($139 million annually).

Table 23

Selected Strategies With and Without Budget Constraint and Increase in Cost Over Without Case*

Borough	Selected Strategy Without	With	Cost Increase ($Million)
Bronx	≥2	≥2	0
Brooklyn	≥3	≥3	0
Manhattan	≥3	≥4	4.9
Queens	≥2	≥2	0
Staten Island	≥1	≥1 or ≥2	0.2
NYC Total**	≥2	≥3	9.3

* ICF = 2.0,DR = 3 percent, Table 10 input costs.
** Assuming uniform strategy applied to all boroughs.

resembled the results for type II strategies, since replacement of the backlog of pipes would be postponed until a later year(s) in the simulation.

148. The budget constraint had little effect on the type II strategies, since they did not call for replacement of large numbers of mains in any one year.

Annual Costs

149. The results shown in the previous sections presented only the "bottom line"; the present values of costs over a 50-year period. The actual amount spent during each of the 50 years, however, is far from uniform. In general, for the policies based on numbers of breaks (type I strategies), the amount spent during the first few years is much larger, even without the effect of discounting. Two factors account for this fact: (a) the systematic replacement of 6-in. pipes is expensive, and (b) for aggressive replacement strategies, the backlog of poor in-place pipes is replaced during the first year of the simulation. The effect of removal of 6-in. pipes is seen over the first 10 years of the simulation (in all cases when 6-in. pipe was removed,

it was removed at a rate of 10 percent per year). The results for more aggressive strategies require much greater expenditures during the earlier years. This result is logical since the backlog is greater for strategies that replace more pipes. Figure 14 shows a typical trend in annual expenditures. The results are for Brooklyn, using an ICF of 2.0. For this figure, values for every 5 years were plotted, resulting in a curve that is not as smooth as the results actually were. The plot shows the undiscounted annual costs for two strategies: a relatively aggressive one (replace pipes with two or more breaks) and a more passive one (replace pipes with four or more breaks). The aggressive strategy exhibits a continual decline from a very high first-year cost. The passive strategy shows a gradual increase in costs, after some fluctuations resulting from the replacement of 6-in. pipes.

150. A similar analysis for a type II strategy (removal based on a percentage) is shown in Figure 15. The plot shows two strategies: removal of 0.1 percent of the system (passive) and removal of 1 percent (aggressive) of the system each year. For both of the type II strategies no special attention

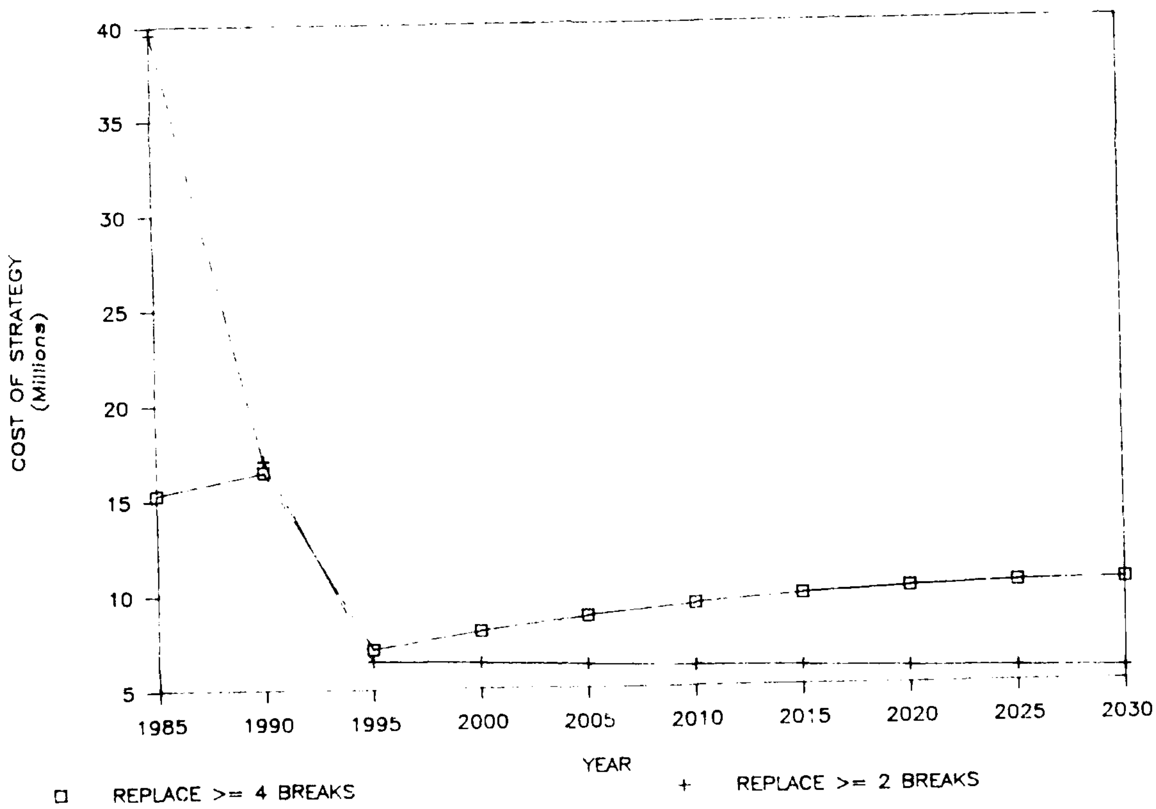


Figure 14. Annual costs (undiscounted) for two type I strategies for Brooklyn (ICF = 2.0, Table 9 input costs)

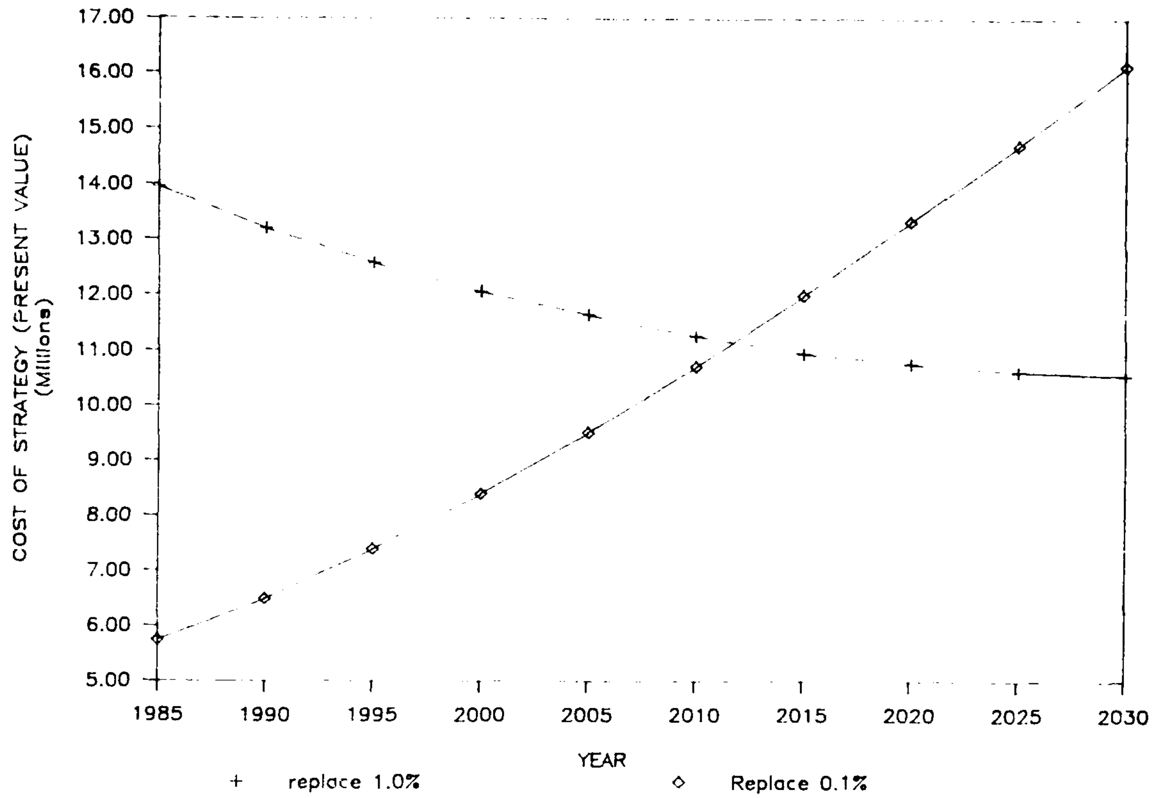


Figure 15. Annual costs (undiscounted) for two type II strategies for Brooklyn (ICF = 2.0, Table 9 input costs)

was paid to 6-in. mains. Consequently, the curves do not have drastic fluctuations during the first 10 years of the simulation. The results show that the more aggressive strategy costs more during the initial years; however, the annual costs drop during successive years. The reverse is true for the less aggressive strategy. The rise in the costs of the passive strategy and the drop in the costs of the aggressive strategy reflect the rise and drop, respectively, in the cost of repairing breaks in both cases.

151. The annual (undiscounted) repair and replacement costs over the period of the simulation provide interesting results. Figure 16 shows these curves for two of the strategies: (a) replace pipes with two or more breaks and (b) replace pipes with three or more breaks. When these two strategies were applied to Brooklyn with an ICF of 2.0, costs were very close; $218.4 and $217.1 million, respectively. The curves in Figure 16 reveal some interesting features. For both strategies, the replacement costs are high during the first year, accounting for the replacement of a backlog of pipes with several breaks. As would be expected, the first year replacement cost for the more

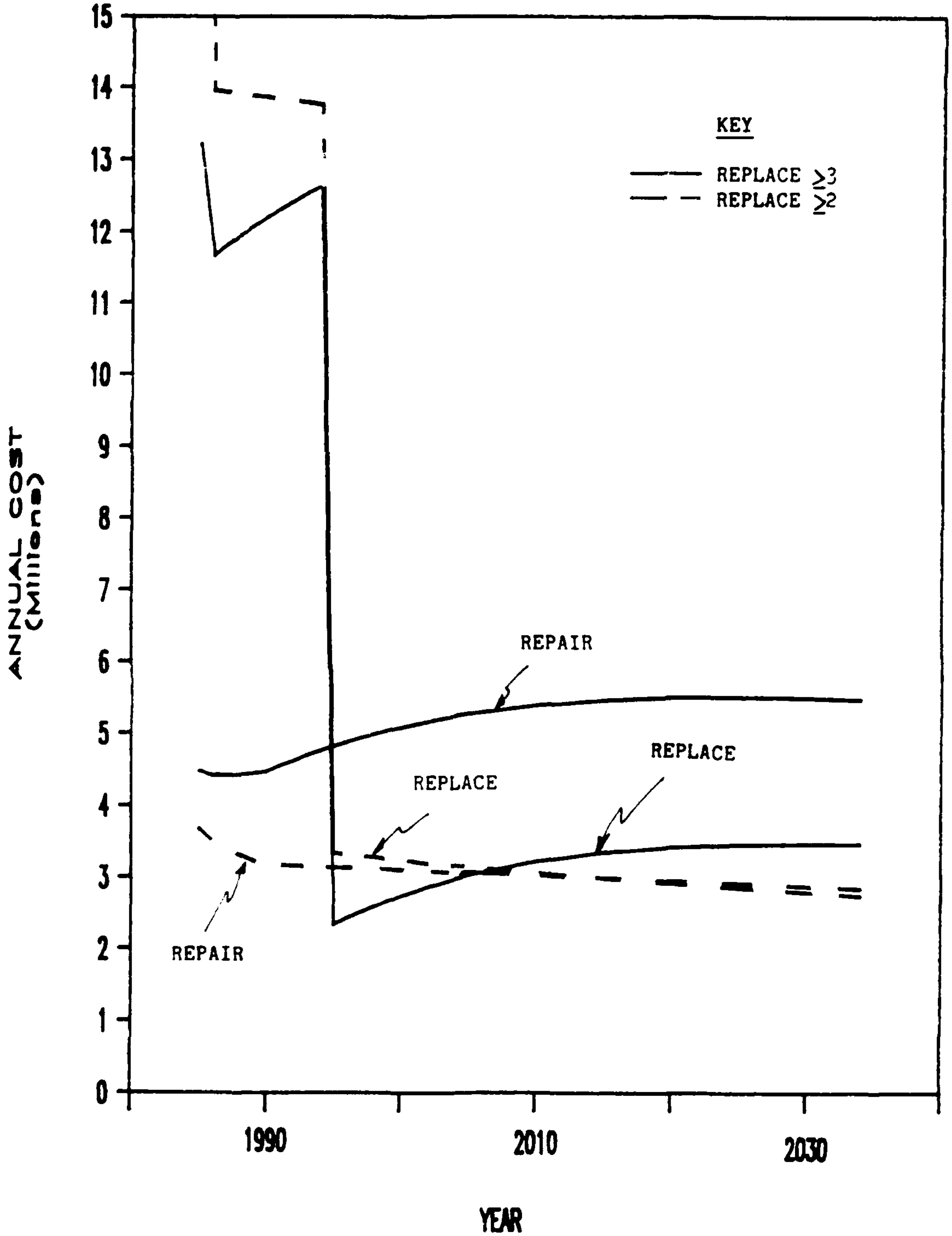


Figure 16. Annual repair and replacement costs (undiscounted) for two strategies for Brooklyn (ICF = 2.0, Table 9 input costs)

aggressive strategy is much higher ($35.9 million). Both strategies also show the large costs associated with replacing 6-in. mains. These costs are represented by the high portions of the replacement curves during the first 10 years.

152. A basic difference between the two strategies, however, is that the repair and replacement costs both decrease over time for the more aggressive strategy and both increase for the less aggressive strategy. For the aggressive strategy, the decrease in the repair curve is logical because the system is gradually being improved. The decrease in the replacement curve also makes sense because the system is improving and therefore there are fewer poor pipes to replace. For the less aggressive strategy the opposite is true. The system is not being renewed as quickly, and the strategy does not keep up with the break rate, resulting in an increase in repair costs. Recall that the aging rate of newly placed pipes is less than that of old pipes. The increase in replacement costs can be explained in the same way; since pipes are being allowed to remain in place until they have had three breaks, their break rate has increased to the point where the replacement strategy cannot keep up. This comparison between the two strategies is noteworthy, because at first glance, the two were almost equal; present costs were very close. Discussion of the resulting quality, or integrity, of the distribution system is found in the next section.

Distribution System Integrity

153. An important factor that has not been discussed to this point is the condition of the distribution system resulting from application of a strategy. As would be expected, less aggressive strategies result in distribution systems that have higher break rates. To assess the condition of the system resulting from the application of a strategy, the break rate was addressed during the simulation period, and in particular, at the end of the 50-year study period.

154. The change in the break rate for the least-cost type I strategies for each of the five boroughs is shown in Table 24. Notice that the projected break rate without the budget constraint for Staten Island (0.001) is the result of the one-or-more break strategy that was applied to obtain the least cost. This strategy assigns the break rate for new pipes (0.001 breaks/block)

Table 24

Current and Projected Break Rates (in Breaks/Block) for the Least-Cost Type I (Number-of-Breaks) Strategies

Borough	Current Break Rate	Projected Break Rate (after 50 years) Without Budgetary Constraint
Bronx	0.403	0.136
Brooklyn	0.312	0.258
Manhattan	1.296	0.261
Queens	0.255	0.139
Staten Isl.	0.106	0.001

to those mains in the zero-break group. Because this strategy acts in this manner, the final break rate is very close to the break rate for new mains (0.001 breaks/block) and is much lower than the current break rate.

155. To better illustrate the change in break rate over time, two type I strategies for Brooklyn are shown in Figure 17. Note that the fluctuations during the early years are due to replacement of 6-in. mains and also that the discrepancy in break rates during the first year is due to the fact that the simulation reports results at the end of the first year. As can be seen from this figure, the more aggressive strategy results in a gradual decrease in the break rate, while the opposite is true for the more passive strategy. The aggressive strategy results in an annual break rate for Brooklyn of 0.00519 breaks/block/year after 50 years, while the passive strategy results in a break rate of 0.01494 breaks/block/year, almost 2-1/2 times higher. These two break rates correspond to approximately 110 and 317 breaks, respectively, during the last year of the simulation. These trends are true for the other boroughs as well.

156. From these results it is clear that the most aggressive strategy will result in the most durable system. However, at some point the cost of attaining a highly sound system becomes excessive. The tradeoff between the integrity of the distribution system and present costs is illustrated in Figure 18. Each point in the graph represents a different strategy, ranging from most aggressive on the left (replace all pipes that have had one or more

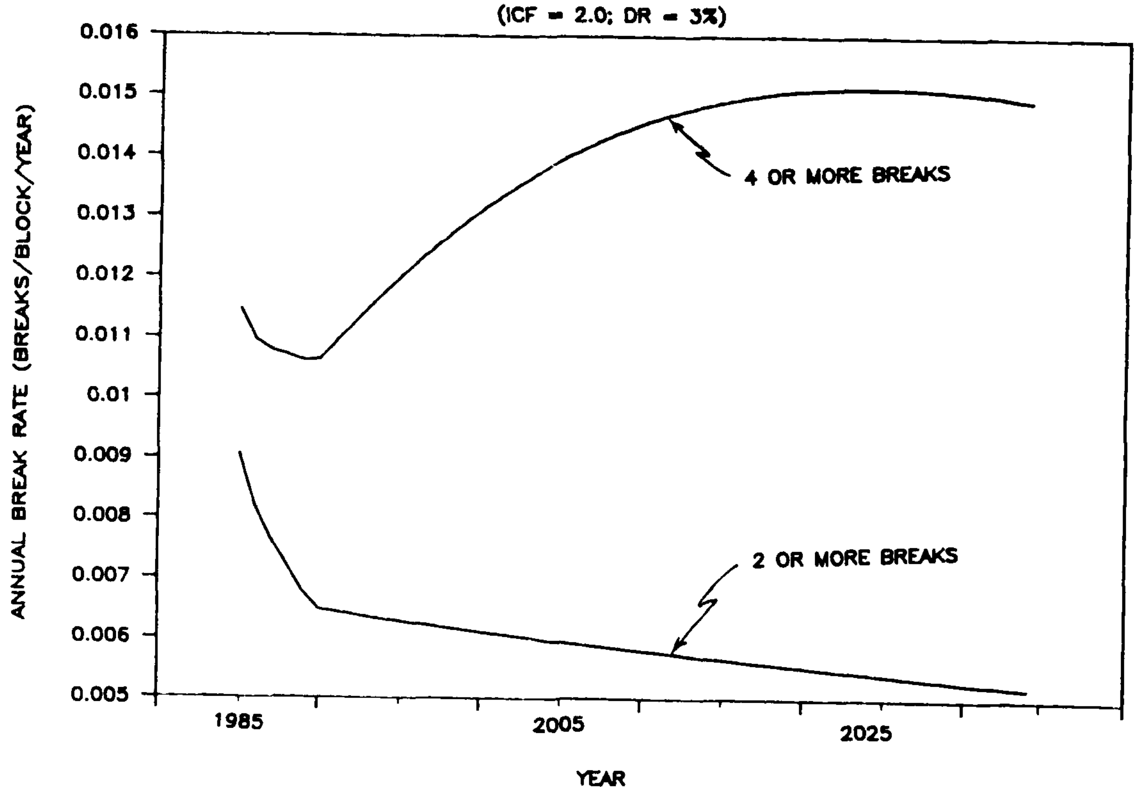


Figure 17. Changes in break rate over the 50-year simulation period for aggressive and passive type I strategies for Brooklyn (ICF = 2.0, Table 10 input costs)

breaks) to the least aggressive on the right (do nothing). As would be expected, current costs are high at either extreme of the scale. In other words, excessively aggressive or passive strategies result in high costs. An aggressive strategy results in a system with a very low break rate, but at a large cost of replacement. A passive strategy, resulting in a high break rate, is not expensive to institute, but the cost of repairing breaks is excessive. Since low cost and low break rate values are desired, both the ≥4 and DN strategies are inferior to the ≥2 and ≥3 strategies. In terms of "aiming for an ideal" break rate, the results shown in Figure 18 would indicate a rate between 0.1 and 0.2 breaks per block (at year 50). It should be remembered, however, that this result is for an inflation-adjusted DR of 3 percent and an ICF of 2.0.

157. Another means of addressing the effect of a replacement policy is to determine the age of the system. Over the course of the simulated 50 years, the average age of the system will change. How much the system ages

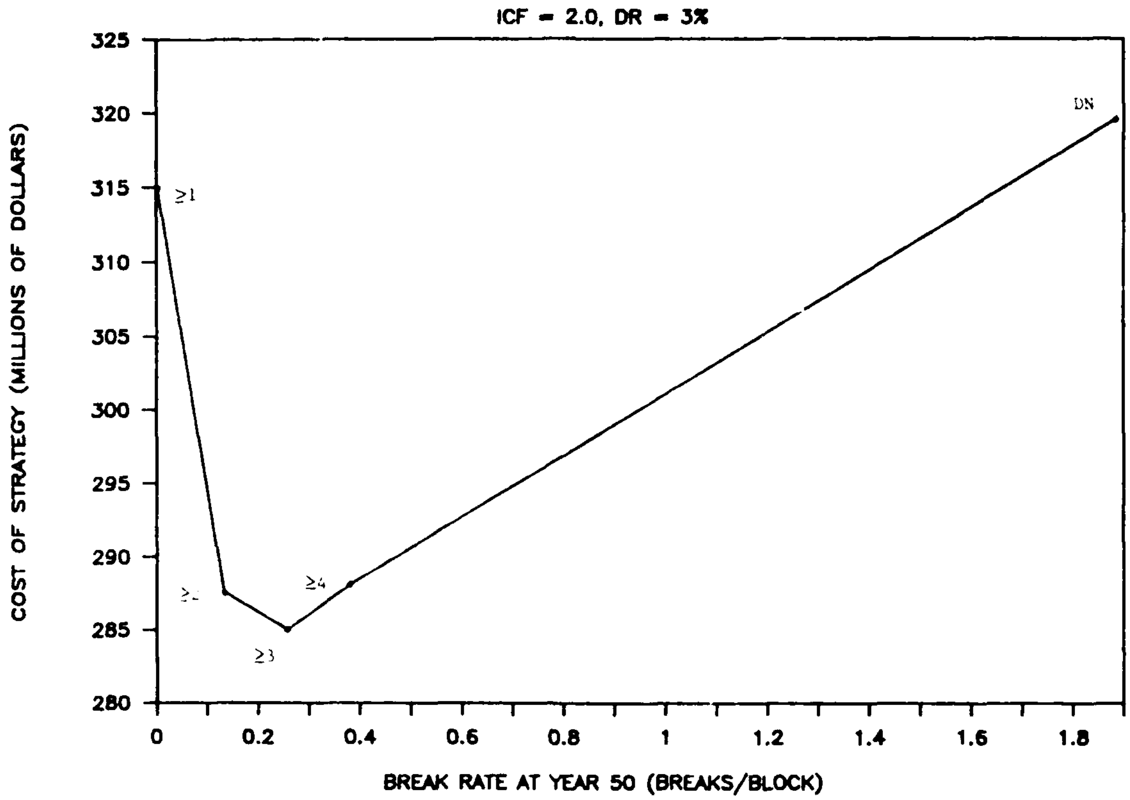


Figure 18. Cost of repair and replacement for type I strategies showing tradeoff between cost and integrity for Brooklyn (ICF = 2.0, DR = 3%, Table 10 input costs)

depends on how aggressive the applied strategy is. Clearly, a do-nothing strategy (with no removal of 6-in. mains) will result in a system that is 50 years older. Because a more aggressive strategy introduces new pipes, the average age of the system will not grow as quickly.

158. One way to observe the change in age is to observe how mains move from older age groups to newer ones. Figure 19 illustrates the effect that application of different strategies has on the portion of mains remaining in the ground (i.e. remaining in their original age category). Although the total number of mains in each borough remains constant during the simulation period, the number of mains shifts to different (future) bundles. As would be expected, the most passive or do-nothing strategy produced the least changes in the distribution of mains in the different bundles. The do-nothing strategy replaces 6-in. mains like the other type I strategies, so 100 percent of the mains that were in place before the simulation began are not in place afterwards. With increasing aggressiveness, the bundle distribution of mains

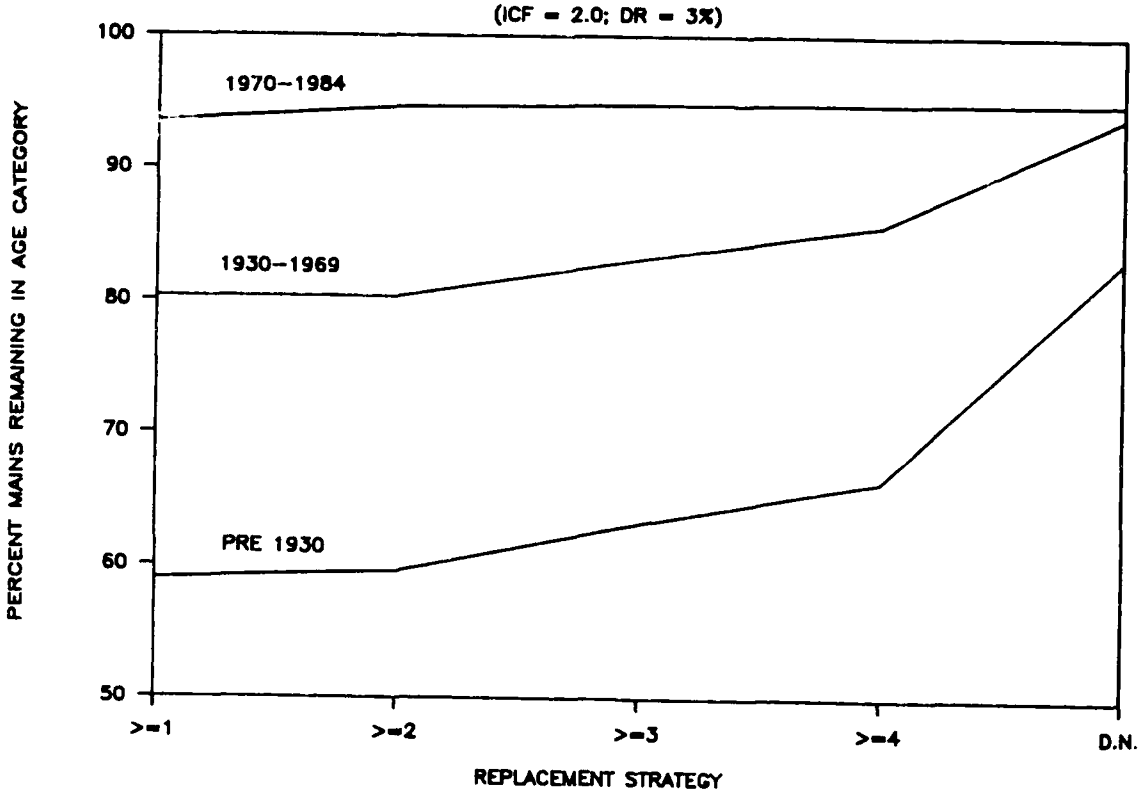


Figure 19. Effect of different type I strategies on the percent of mains remaining in original age groups for Brooklyn (ICF = 2.0, DR = 3%, Table 10 inpuւ _osts)

changed so that there were many new mains. However, even with the most aggressive one-or-more break strategy, many mains remained in the oldest age group at the end of the 50-year simulation period.

159. Figure 20 illustrates the aging concept in a different way by plotting the average age (at the end of the 50-year simulation period) of each borough's system. The average age was determined by assigning the median age to each age category and weighting the age by the length of mains in the category. After the 50-year simulation, average ages for the pre-1930, 1930-1969, and post-1970 periods were 135.5, 85.5, and 58 years, respectively. All mains that were installed to replace 6-in. mains were assigned an average age of 45 years since they were always replaced in the first 10 years of the 50-year simulation. The rest of the newly replaced mains were assigned an average age of 25 years, assuming (although somewhat unrealistically) that they were replaced evenly over the course of the simulation. The most notable aspect in Figure 20 is the relatively low average age for Manhattan. This

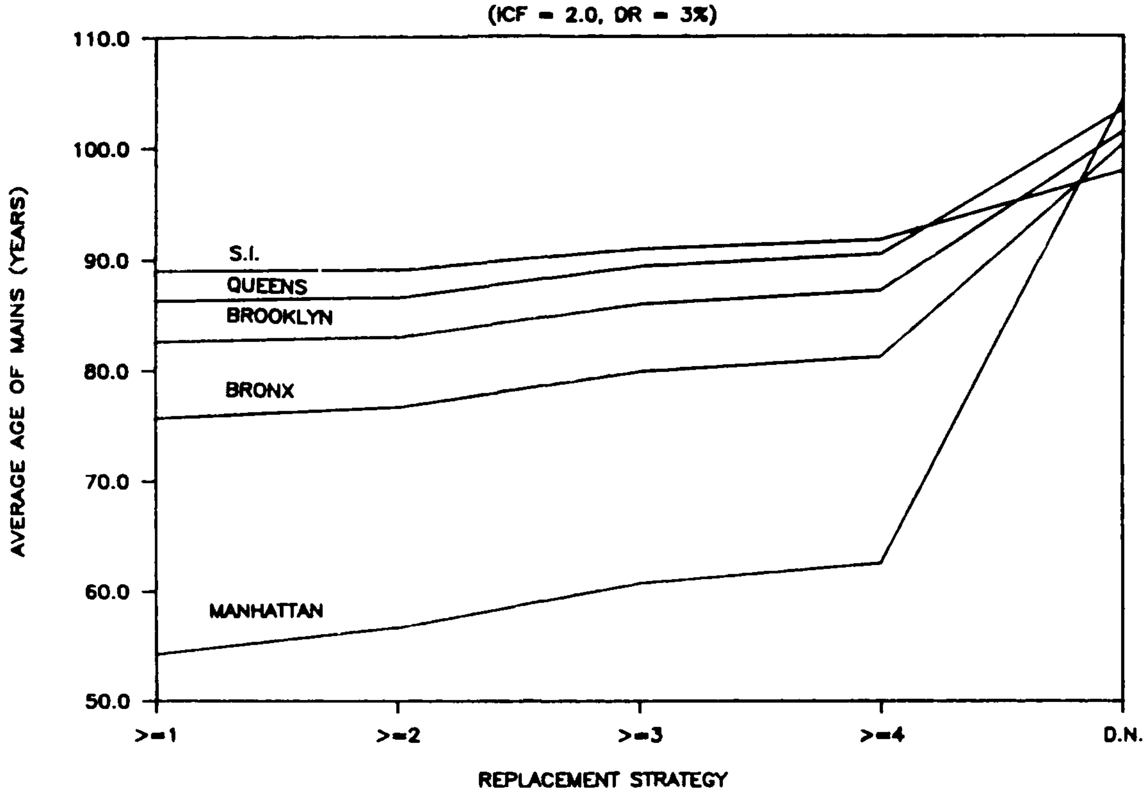


Figure 20. Average age of mains after application of type I strategies (ICF = 2.0, DR = 3 percent, Table 10 input costs)

result is explained by the fact that Manhattan's break rate is very high, particularly for older pipes. Because of the high break rate a fairly large number of mains are replaced (even for somewhat passive strategies), and a large portion of these are from the pre-1930 age category.

PART VI: SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

160. The intent of this report is to address the problem of water main breakage in New York City and to analyze policies for reducing the costs associated with maintaining the City's distribution system. Analysis of the problem in the five boroughs that make up New York City was done in detail in four previous reports. Part II of this report summarized the findings of those documents and highlighted similarities and differences among the boroughs. The major goal of this report, however, was to study policies for maintaining the City's water distribution system in terms of the costs involved and the resulting integrity of the system.

161. A mathematical simulation model was developed to analyze different pipe replacement strategies under a variety of conditions. Two basic types of strategies were tested: (a) replacing pipes based on the number of breaks a pipe has experienced, and (b) replacing pipes based on a prespecified percentage of the distribution system. Determination of the condition of pipes was based on historical records of the break rates of pipes for different boroughs, pipe diameters, and the period in which the pipes were laid. Each year of the simulation kept track of the numbers of mains replaced as a result of the application of a strategy, the associated cost, the number of breaks expected for a bundle of mains, and the associated break repair cost. Annual costs were discounted to present value and summed to determine the total cost for the strategy for the 50-year simulation period.

162. Since 1970 New York City's Bureau of Water Supply has followed a strategy that involves: (a) the gradual removal of all 6-in. mains and replacement with larger diameter pipe, and (b) the removal of any main segment that has had two or more breaks over its history.* This policy was compared to other strategies using the simulation to determine relative total costs and resulting integrity of the distribution system.

163. The overall intent of the simulation was to address the long-term planning necessary to insure a sound water distribution system at a reasonable

* Comments by the City of New York on the draft of this report indicated an additional policy of replacing pre-1930 mains in joint contracts.

cost. The level of detail is not sufficient to determine which specific main segments should be replaced. The simulation can point to bundles of pipes with similar characteristics, so that they might receive more emphasis and/or closer scrutiny. The simulation only considers the physical integrity of mains. Other factors may influence the decision to replace a pipe. These include the carrying capacity of main segments, and possible street repaving. Including these factors in what can be called opportunistic decision making should be done at the detailed level when individual pipe segments are being considered.

Conclusions

164. The Bureau of Water Supply should continue to aggressively approach the replacement of water mains in all five boroughs. The current policy of replacing main segments that have had two or more breaks is a sound approach. This conclusion is based on costs and resulting system integrity, under a range of circumstances. It is impossible to select one policy that will always be optimal, given uncertain economic conditions. Based on an anticipated inflation-adjusted DR of 3 percent and assuming that indirect costs associated with main breaks are equal to the direct costs, the policy of replacing mains with two or more breaks is the least-cost approach.

165. In addition, a general conclusion can be drawn concerning selection of an appropriate policy, even if the values of the DR and indirect break costs are somewhat uncertain. Increasing the value of the DR tends to favor less aggressive strategies, while increasing the indirect break costs tends to do the opposite. Two policies are good, in that if either of them were selected, they would not be much more expensive than the optimal for any DR in the range of 1-7 percent. These two policies are replacing mains with two or more, and three or more breaks. Further, if the indirect costs associated with a break are greater than 50 percent of the total (direct and indirect) break (and subsequent repair) costs, then the two-or-more policy would be advantageous over the three-or-more policy.

166. The ability to select, under uncertain circumstances, a policy that is likely to be close to the optimum is valuable information. The results of this research show that within the range of input parameters

assumed, the policy of replacing mains that have had two or more breaks is a very sound approach.

167. Clearly, the two-or-more break policy must not be approached rigidly, but sound engineering judgment should be incorporated using whatever information is available for general categories of pipes and on specific main segments. For example, a pipe segment that was broken twice by a careless construction crew should not be blindly slated for replacement. Also, early replacement of a main whose breakage would cause considerable damage should take precedence.

168. Application of an annual city-wide budget constraint of $60 million, for replacement of all but 6-in. mains, did not have a large impact on the total cost or strategy chosen. If a lower annual budget was applied, aggressive replacement of mains, particularly during the first year, would be curtailed. As a result, total costs would be higher, and less aggressive strategies would fare better. The implication is that, in the long run, deferring replacement due to insufficient funds actually costs more money.

169. The conclusions in the previous paragraphs concentrate on replacement strategies that are based on the number of breaks that a main has had. This type of strategy is superior to an approach that designated removal of a fixed percentage of mains. Costs for the least-cost number-of-breaks strategy were considerably less than the least-cost percentage strategy. In addition, several interesting observations resulted from the comparison of the two types of approaches. The number-of-breaks strategies are based on the condition of the system. As such, application of these types of strategies, particularly the more aggressive ones, resulted in replacement of a large backlog of mains during the first year. The percentage approaches, by their nature, removed a set percentage each year. Application of a more restrictive budget constraint would have the effect of curtailing the amount of replacement during the first year, and would therefore affect the results of aggressive, number-of-break strategies. It is likely that as budget constraints become more and more restrictive, results for the number-of-break strategies would resemble more closely those for the percentage strategies.

170. Applying a strategy uniformly across all boroughs, all main diameters, and all mains laid in different periods will result in costs that are higher than if nonuniform policies were to be implemented. In general, though, the savings are not great and may not be worth the administrative

effort of implementation. Deviation from a city-wide uniform policy would result in savings if Manhattan and Brooklyn were to adopt less aggressive strategies. However, the loss in system integrity may not justify the cost savings. These results, however, must be viewed in the overall context; Manhattan and Brooklyn have high replacement costs, particularly for large-diameter mains. In addition, break and repair costs might be higher in these boroughs, a possibility that was not included in the simulations. Also, many mains in Manhattan need replacing for reasons in addition to poor integrity: primarily, to increase carrying capacity.

171. If different strategies are applied to different categories based on main diameter, only small savings in total cost are evident. However, in all boroughs, least-cost policies applied more aggressive strategies to small-diameter mains and more passive strategies to large-diameter mains.

172. For most boroughs, nonuniform application of strategies to older mains (those installed before 1930) did not yield any significant savings over uniform application. Again the only exception was Manhattan, where more aggressive replacement of pre-1930 mains resulted in a lower total cost.

173. When considering the integrity of the system after application of a strategy, it is logical to expect that the most aggressive strategies result in systems with the lowest break rate. In general, aggressive strategies result in a break rate that gradually decreases each year. The opposite is true for more passive strategies. However, there is a trade-off between the desire to decrease the overall break rate and the goal of minimizing total costs. A moderately aggressive strategy of replacing mains that have had two or more breaks does the best job of minimizing costs and approaching a low break rate.

174. The intent of this report is to assess main replacement strategies in the context of long-term planning. The results are presented in that context, considering a 50-year planning horizon. Based on the results, two aspects warrant further consideration: (a) short-term versus long-term planning, and (b) planning versus operation/maintenance strategies.

175. The results of applying the number-of-break strategies revealed that a large backlog of mains were being replaced during the first year of the simulation. This backlog represents those mains considered sub-standard when compared to the strategy being applied. If replacement of 6-in. mains is ignored, the number of mains replaced after the first year is far less than

the backlog replaced during the first year, particularly for aggressive strategies. This result raises the question of whether two policies should not be addressed: a short-term policy aimed at removing the backlog of mains over a few years, followed by a policy that attempts to maintain the system at an acceptable level of integrity.

176. The second consideration addresses planning on a year-to-year, or even day-to-day basis, and is closer to actual implementation of the policy or operation/maintenance strategies. Several of the results showed that nonuniform application of the policy yielded slight savings in total cost. The nonuniform approach would be advantageous when addressing day-to-day decisions. Application of different strategies to different categories of mains based on diameter provides the best example. If both an 8-in. and a 20-in. main had recently incurred their second breaks, and a two-or-more break policy was being followed, both mains should be scheduled for replacement. However, shortages in personnel and/or money may restrict action to one main. If all other aspects are equal, the smaller diameter main should be replaced first.

Recommendations

177. New York City's Bureau of Water Supply should continue to replace water main segments once they have experienced their second break. This policy results in a low total cost and a system of sound integrity. The Bureau should also consider applying less aggressive strategies to larger diameter mains, particularly in Manhattan and Brooklyn, where replacement costs are very high. In addition, older mains in Manhattan should be considered for a slightly more aggressive strategy. Actual implementation of these nonuniform approaches might easily be accomplished at the scheduling stage when priorities are assigned to specific pipe segments.

178. To assist in future decision making, the Bureau should consider adopting a computerized data maintenance and retrieval program for pertinent information on breaks and their repair. These data would then be available to provide support for repair/replacement decisions.

REFERENCES

Clark, R. M., Stafford, C. L., and Goodrich, J. A. 1982 (Oct). "Water Distribution Systems: A Spatial and Cost Analysis," Journal of the Water Resources Planning and Management Division, ASCE, Vol 108, No. WR3.

Hanke, S. H., Carver, P. H., and Bugg, P. 1975 (Aug). "Project Evaluation During Inflation," Water Resources Research, Vol 11, No. 4.

Shamir, U., and Howard, C. D. D. 1979 (May). "An Analytic Approach to Pipe Replacement," Journal of the American Water Works Association, Vol 71, No. 5.

US Army Engineer District, New York. 1980. "New York Water Supply Infrastructure Study; Volume I: Manhattan," New York.

US Army Engineer District, New York. 1984. "New York Water Supply Infrastructure Study; Volume II: Brooklyn," New York.

Walpole, R. E. 1974. Introduction to Statistics, MacMillan Publishing Co., New York.

Walski, T. M., and Pelliccia, A. 1982 (Mar). "Economic Analysis of Water Main Breaks," Journal of the American Water Works Association, Vol 74, No. 3.

Walski, T. M., and Wade, R. 1987. "New York Water Supply Infrastructure Study; Volume III: The Bronx and Queens," Technical Report EL-87-9, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Walski, T. M., Wade, R., and Sharp, W. W. 1988. "New York Water Supply Infrastructure Study; Volume IV: Staten Island," Technical Report EL-87-9, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

APPENDIX A: NOTATION

a	Regression coefficient (expected break rate in 1933), breaks/yr/mile
b	Rate of increase of breakage, 1/yr
b'	Aging rate for the existing pipes (with no new replacement) for the bundle ($years^{-1}$)
B_h	Number of breaks over history (observed)
B_n	Number of breaks for the bundle if pipes were removed and none were replaced
e	Base of the natural logarithms
f	Inflation rate
f_i	Higher break factor for pipe groups with one or more breaks
i	Number of breaks for the break group
i	Discount (interest) rate
J	Break rate in year t, breaks/yr/mile
N	Number of blocks in the bundle initially
N_i	Number of main segments with i breaks in break group
ΔN	Number of blocks removed from the bundle for replacement
$P(x)$	Probability of having x breaks in a main segment, for the life of the main
$P'(y)$	Probability of having y breaks in a main segment in 1 year
r	Inflation-adjusted discount rate
t	Time, years
u	Mean number of breaks in a main segment for the life of the main, for the bundle, (breaks per main segment)
u'	Revised break rate (breaks/block) following application of strategy (p. 31); break rate from the update subroutine (breaks/block) (p. 33)
u''	Break rate after aging (historical break rate)
u_h	Break rate that is observed over history for the bundle (removed pipes are replaced with new pipes) (breaks/block/year)
u_n	Break rate for the bundle when pipes are removed but none are replaced (breaks/block/year)

u_0 Initial break rate for the bundle

u_R Break rate of those pipes removed for replacement (breaks/block/year)

w Annual break rate

w_i Break rate for break group i

w_0 Break rate for the zero-break group (breaks/block/year)

x Number of breaks over the life of the main

y Number of breaks during one year

APPENDIX B: USER'S MANUAL FOR THE WATER MAIN REPLACEMENT MODEL

PART I: GENERAL INTRODUCTION

Background

1. This manual provides a brief description of the input necessary to run the Water Main Replacement Model (WMRM). It is intended for use by someone who is familiar with the WMRM which is described in the Technical Report that precedes this appendix. This manual will guide the user through the data input and testing of different strategies.

Programs

2. There are two different models included on the accompanying floppy disk. The first, entitled WMRM.FOR, contains the Fortran code of the single-run version of the WMRM. The second model is a multiple-run version of the WMRM and is in the file RUNS.FOR. The multiple-run version incorporates the single-run version and allows the user to make several runs, each with different input data.

3. Both programs were created in VAX Fortran and will run on a Digital VAX system. At the time of programming, it was desirable to make the WMRM as flexible as possible and large arrays were used. A PC with over 705K of RAM would be necessary to run the WMRM as it is now coded, but the program could be reduced in size by shrinking some of the arrays. This would enable the single-run version to run on a PC with a 640K RAM. The Fortran code might also have to be modified slightly because VAX Fortran is slightly different than other types of Fortran.

Applicability

4. The programs were designed for application to the five boroughs of New York City. Modifications to the code would be necessary if data from another system were to be used. The programs are based on data for 12 bundles of mains, categorized by period of installation and diameter. The categorizations are:

Diameter group 1: 6-in. mains
Diameter group 2: 8-in. mains
Diameter group 3: 12-in. mains
Diameter group 4: 16- to 24-in. mains

Age group 1: those installed before 1930
Age group 2: those installed between 1930 and 1969
Age group 3: those installed after 1969

Input Data

5. Data utilized by the programs (all internal default values and some user-input values) are specific to New York. Files containing the length of mains and break rates according to diameter of pipe and period of installation are contained on files for each of the five boroughs:

Bronx.dat
Brk.dat
Manhattan.dat
Queens.dat
Statenisl.dat

These data files are included on the accompanying disk and are called internally by the program.

6. Designation of the strategy to be applied requires responses to several prompts. A brief overview will help the user understand the meaning of these prompts. Two general options are available: a) replace all pipes that have greater than a prespecified number of breaks, or b) replace a prespecified percentage of pipes in each borough. These two options can be further refined at the user's request so that different diameter categories and/or different age categories can have different prespecified values, or policies, applied. The choice of strategy is specified by designation of percentages and/or a number of breaks for diameter groups and age groups. This designation is as follows:

a. For each diameter group the user specifies either: (1) a fraction of main segments to be replaced, or (2) a number of breaks equal to or above which all main segments will be replaced.

b. For each age group the user specifies a fraction of main segments to be replaced (for example, 10 percent of mains laid before 1930).

This approach allows considerable flexibility. Examples of some strategies that could be pursued are listed on the next page showing how a user would specify parameter values. For example, the user may want to test a strategy of replacing all mains below 16 in. in diameter when they have had one or more breaks and all those with 16-in. diameter and greater that have had two or more breaks. The user would enter this strategy with specifications of 100 percent for each of the age categories and values of one and two for those main segments with diameters of less than, equal to, or greater than 16 in., respectively. If the user wishes to use the same break values for the diameter categories, but concentrate more on older pipes, different percentages could be specified for the age categories. For example, replace 50 percent (of those pipes with breaks equal to or greater than the specified number) for the new and middle-age categories and 100 percent of the old-age category.

Table B1

Examples of Strategies and Appropriate Input Designation

	User Input		
Possible Replacement Strategy	Portion of Age Category	Portion of Diam. Category	No. of Breaks
Replace all pipes below 16 in. that have had ≥ one break and all above 16 in. that have had ≥ two breaks	1.0 for all categories	NA*	1 (< 16") 2 (≥ 16")
Replace 50% of all pipes laid before 1930 and 5% of all others	0.5 for all < 1930 and 0.05 for all ≥ 1930	1.0 for all	NA
Replace 20% of all pipes with ≥ one break	0.2	NA	1
Replace 10% of 6-in. mains and all others that have had two or more breaks	1.0 for all categories	0.1 (for 6") NA for others	2 (> 6")

* NA = Not applicable for strategy selected.

PART II: SINGLE-RUN SIMULATION (WMRM)

The descriptions below will follow through the sequence of prompts supplied by the computer and possible responses by the user. In addition, where appropriate, explanations and comments are added. The following assumes the user has called the program by executing the RUN command. User input is given in boldface letters and program prompts are in CAPITAL LETTERS.

Input

Prompt: INPUT NAME OF BOROUGH

Permissible responses:

BRONX
BROOKLYN
MANHATTAN
QUEENS
STATEN ISLAND

Note: Responses must be in capital letters and spelled correctly.

Prompt: INPUT THE PERCENT OF PIPE TO BE REPLACED FOR GROUP 1.
ENTER 1.1 IF YOU WISH TO USE A MAXIMUM
NUMBER OF BREAKS AS THE REPLACEMENT CRITERIA.

Possible responses: **0.1 - 1.0 or 1.1**

Explanation:

Diameter group 1 refers to 6-in. mains which are automatically replaced during early years of the simulation.

Prompt: INPUT THE PERCENT OF PIPE TO BE REPLACED FOR GROUP X.
ENTER 1.1 IF YOU WISH TO USE A MAXIMUM
NUMBER OF BREAKS AS THE REPLACEMENT CRITERIA.

Possible responses: **0.1 - 1.0 or 1.1**

Explanation:

This prompt is repeated three times with x being equal to 2, 3, or 4 (referring to diameters of 8, 12, or 16 to 24 in. respectively). A fraction response (0.0 - 1.0) indicates the fraction of pipes (for diameter group x) that will be replaced each year. A response of 1.1 indicates that the user wants to test a maximum number of breaks strategy rather than a percentage of all pipes in diameter group x.

Example: If **0.01** is entered for group 2 (8-in. mains) one percent of the worst 8-in. mains (those with the most breaks) will be replaced each year. Similarly, if 0.01 is entered for groups 3 (12-in. mains) and 4 (16- to 24-in. mains), one percent of the worst mains in each of these groups will be replaced each year.

Possible Prompts:

INPUT THE MAXIMUM NUMBER OF BREAKS A PIPE WILL HAVE
EQUAL TO OR GREATER THAN THIS NUMBER THEY WILL BE REPLACED
ENTER MAXIMUM NUMBER OF BREAKS FOR DIAMETER GROUP X.

Permissible Responses: 1.0, 2.0, 3.0, 4.0, 5.0

Explanation:

This prompt will appear only if 1.1 was input by the user for the appropriate diameter group during the previous series of prompts. This prompt may appear three times for x = 2, 3, and/or 4. The input responses of 1.0, 2.0, 3.0, and 4.0 represent the number-of-breaks replacement policy that is applied to diameter group x (e.g., 2.0 will indicate that all pipes in diameter group x which have had two or more breaks will be replaced). A response of 5.0 will invoke a do-nothing strategy.

Example: The user can apply a two-or-more break strategy to all diameter groups by entering 2.0 for group 2, 2.0 for group 3, and 2.0 for group 4. If the WMRM is to apply different number-of-break strategies to different diameter groups, different numbers can be input for each diameter group. For example, if the user replies to the prompt ENTER MAXIMUM NUMBER OF BREAKS by entering 2.0 for group 2, 3.0 for group 3, and 4.0 for group 4, a two-or-more break strategy will be applied to the 8-in. mains, a three-or-more break strategy will be applied to the 12-in. mains, and a four-or-more break strategy will be applied to the 16- to 24-in. main group.

Note: The user will not be prompted for a value for group 1 because this is the 6-in. main group and a fraction of mains to be replaced each year must be specified for it.

Possible Prompts:

INPUT THE FRACTION OF PIPES TO BE REPLACED FOR AGE GROUP Y

Permissible responses: 0.0 or 0.001 - 1.0

Explanation:

This prompt will appear up to three times for Y = 1, 2, and/or 3 (representing the three age groups, ≤1929, 1930-1969, ≥1970, respectively). If the effect of the age group of mains is not going to be tested, then the answer to this prompt will be 0.0 for each age group. Responding with a fraction will indicate the fraction of mains that have had x or more breaks (where x was specified earlier) in age group Y that will be replaced.

Example: Any age group can be tested by replacing only a fraction of its specified length of mains. For instance, if a two-or-more break strategy is specified above, all of the mains with two or more breaks will be replaced so long as the answer to the prompt 'INPUT THE FRACTION OF PIPES TO BE REPLACED FOR AGE GROUP Y' is 0.0 for each age group. Only half of the mains with two or more breaks will be replaced if the answer to the prompt 'INPUT THE FRACTION OF PIPES TO BE REPLACED FOR AGE GROUP Y' is 0.5 for all age groups. If 0.0 is specified for age group 1 (pre-1930) and 0.5 is specified for age group 2 (1930-1969) and age group 3 (post-1970), then half of the mains slated to be replaced under the two-or-more break strategy will be replaced for age groups 2 and 3 and all of the mains slated to be replaced under the two-or-more break strategy will be replaced for age group 1 (pre-1930).

Prompt: INPUT THE INDIRECT COST WEIGHTING FACTOR.

Permissible responses: 1.0 - 9.9

Explanation:

The ICF is multiplied times the direct cost of a break to arrive at a more realistic total cost of a water main break.

Note: Suggested values are in the range of 2.0 to 4.0.

Prompt: INPUT THE INTEREST RATE

Permissible range: 0.01 - 0.99

Note: The interest rate is to be entered as a fraction, so if the prevailing inflation-adjusted interest rate is 3 percent, enter 0.03. The suggested range of interest rates which might be tested is between 0.01 and 0.10.

Prompt: ENTER AN ANNUAL BUDGET (DOLLARS)

Permissible range: 1 - 1e12

Note: This is the annual replacement budget for the borough of interest. It is only the amount allocated for replacing mains and has no impact on repairs that are always assumed to occur. If a budget constraint is not desired, a large budget is input (1xE12 will work).

Prompt: HOW MANY YEARS DO YOU WANT TO SIMULATE? (MAXIMUM = 50)

Permissible responses: 1 - 50 (integers only)

Prompt: WHICH PRINTOUT OPTION WOULD YOU LIKE?
CHOICES ARE:
1 -- ONLY RESULT SENT TO SCREEN
2 -- OUTPUT TO FILE PIPEOUT.DAT.

Permissible responses: 1 or 2

Explanation:

If 1 is entered only the final present value of cost will be output on the screen. If 2 is entered an output file (called pipeout.dat) will be created which shows information about the simulation as it progressed on a yearly basis.

Output

8. The file pipeout.dat lists input and output information for the simulation. Figure B1 shows an example of the output with various notations.

BOROUGH: QUEENS ← DESIGNATED BOROUGH

REPLACEMENT STRATEGY:

FRACTION OF DIAMETER GROUP 1 TO BE REPLACED = 0.100
MAXIMUM # OF BREAKS FOR DIAMETER GROUP 2 = 4.00
MAXIMUM # OF BREAKS FOR DIAMETER GROUP 3 = 4.00
MAXIMUM # OF BREAKS FOR DIAMETER GROUP 4 = 4.00

FRACTION OF AGE GROUP 1 TO BE REPLACED = 1.00
FRACTION OF AGE GROUP 2 TO BE REPLACED = 1.00
FRACTION OF AGE GROUP 3 TO BE REPLACED = 1.00

USER INPUT STRATEGY

PHYSICAL CHARACTERISTICS:

HIGHER BREAK FACTOR FOR GROUP 1 = 1.000
HIGHER BREAK FACTOR FOR GROUP 2 = 5.000
HIGHER BREAK FACTOR FOR GROUP 3 = 10.000
HIGHER BREAK FACTOR FOR GROUP 4 = 15.000
HIGHER BREAK FACTOR FOR GROUP 5 = 20.000

AGEING COEFF. FOR OLD PIPES = 0.040 AGEING COEFFICIENT FOR NEW PIPES = 0.020

PREASSIGNED VALUES

ECONOMIC CHARACTERISTICS: USER SPECIFIED DISCOUNT RATE

THE INTERST RATE = 0.03 THE INDIRECT COST WEIGHTING FACTOR = 2.00 ← USER SPECIFIED ICF

ANNUAL BUDGET = 1.6000000E+07 ← BUDGET CONSTRAINT

DISTRIBUTION OF PIPES AT PRESENT TIME (BLOCKS=440 FEET):

AGE GROUP	6 INCH	8 INCH	12 INCH	16-24 INCH
- 1929	927.7773	4732.239	1991.482	743.3046
1930 - 69	67.35681	4319.784	2451.718	645.9319
1970 - 84	12.42045	515.9635	449.2591	179.8841
1985 -	0.0000000E+00	0.0000000E+00	0.0000000E+00	0.0000000E+00

DISTRIBUTION OF PIPES AFTER SIMULATION (BLOCKS=440 FEET):

AGE GROUP	6 INCH	8 INCH	12 INCH	16-24 INCH
- 1929	0.0000000E+00	3835.051	1736.222	657.6367
1930 - 69	0.0000000E+00	3331.993	2258.106	604.1299
1970 - 84	0.0000000E+00	515.7634	449.2269	179.8818
1985 -	0.0000000E+00	2613.234	443.9079	127.4733

DISTRIBUTION OF MAINS BY BUNDLE, BEFORE AND AFTER SIMULATION

RESULTS:

YEAR	ANNUAL BREAK RATE BRK./BL./YR.	AVERAGE BREAK RATE BRK./BL.	BLOCKS REPLACED BLOCK=440	UNDISCOUNTED COST OF REPLACE	UNDISCOUNTED COST OF REPAIR	UNDISCOUNTED TOTAL COST
1985	0.00948	0.24221	0.1053E+03	0.3891E+07	0.2813E+07	0.6704E+07
1986	0.00929	0.23763	0.1134E+03	0.4201E+07	0.2758E+07	0.6959E+07
1987	0.00910	0.23261	0.1151E+03	0.4267E+07	0.2701E+07	0.6968E+07
1988	0.00909	0.23248	0.1165E+03	0.4333E+07	0.2699E+07	0.7033E+07
1989	0.00911	0.23277	0.1185E+03	0.4401E+07	0.2703E+07	0.7104E+07
1990	0.00911	0.23291	0.1203E+03	0.4469E+07	0.2704E+07	0.7174E+07
1991	0.00920	0.23533	0.1221E+03	0.4538E+07	0.2732E+07	0.7270E+07
1992	0.00941	0.24067	0.1233E+03	0.4607E+07	0.2794E+07	0.7401E+07
1993	0.00962	0.24586	0.1255E+03	0.4676E+07	0.2854E+07	0.7530E+07
1994	0.00981	0.25089	0.1274E+03	0.4744E+07	0.2913E+07	0.7657E+07
1995	0.01000	0.25576	0.2629E+02	0.1012E+07	0.2969E+07	0.3982E+07
1996	0.01019	0.26047	0.2800E+02	0.1080E+07	0.3024E+07	0.4104E+07
⋮	⋮	⋮	⋮	⋮	⋮	⋮
2026	0.01285	0.32377	0.6036E+02	0.2406E+07	0.3813E+07	0.6219E+07
2027	0.01286	0.32912	0.6133E+02	0.2426E+07	0.3817E+07	0.6243E+07
2028	0.01287	0.32939	0.6176E+02	0.2444E+07	0.3820E+07	0.6264E+07
2029	0.01287	0.32957	0.6216E+02	0.2461E+07	0.3822E+07	0.6283E+07
2030	0.01288	0.32968	0.6253E+02	0.2478E+07	0.3823E+07	0.6300E+07
2031	0.01288	0.32971	0.6287E+02	0.2493E+07	0.3823E+07	0.6315E+07
2032	0.01288	0.32967	0.6318E+02	0.2506E+07	0.3822E+07	0.6328E+07
2033	0.01287	0.32956	0.6347E+02	0.2519E+07	0.3820E+07	0.6339E+07
2034	0.01286	0.32939	0.6372E+02	0.2531E+07	0.3818E+07	0.6349E+07
PRESENT VALUE OF TOTAL			0.3190E+04	0.6861E+08	0.8372E+08	0.1523E+09

ANNUAL VALUES (UNDISCOUNTED COSTS)

PRESENT VALUE OF COSTS

Figure B1. Example of pipeout. dat.

PART III: MULTIPLE-RUN VERSION (RUNS)

Introduction

9. In this program the user is prompted to enter ranges of values to be tested by repeated application of the single-run simulation. These ranges are characterized by a lower limit, an upper limit, and a skip factor. The range between the upper and lower limits must always be an integer multiple of the skip factor. In this way, the program will know how many iterations to proceed with or how many different values of a variable to test. The following assumes the user has called the program by executing the RUN command. User input is given in boldface letters and program prompts are in CAPITAL LETTERS.

Input

Prompt: WHICH BOROUGH WOULD YOU LIKE TO TEST?
1 -- BRONX
2 -- BROOKLYN
3 -- MANHATTAN
4 -- QUEENS
5 -- STATEN ISLAND
6 -- ALL BOROUGHS SEPARATELY
ENTER NUMBER OF CHOICE:

Permissible responses: 1, 2, 3, 4, 5, or 6

Explanation:

The user should enter the corresponding number of the chosen borough or 6 if all boroughs are to be tested in one run of the program.

Prompt: WOULD YOU LIKE TO REPLACE PERCENTAGES OF PIPES
OR WOULD YOU LIKE TO REPLACE PIPES WITH MORE THAN
A CERTAIN NUMBER OF BREAKS SINCE THEY WERE LAID?
1 -- REPLACE A PERCENTAGE
2 -- REPLACE MORE THAN A NUMBER OF BREAKS

Permissible responses: 1 or 2

Explanation:

The user should select the number corresponding to the strategy type which is to be tested.

Prompt: WOULD YOU LIKE TO APPLY DIFFERENT STRATEGIES
TO DIFFERENT DIAMETER GROUPS?
1 -- YES
2 -- NO

Permissible responses: 1 or 2

Note: If 1 is selected, the program will ask for a range of percentages to be replaced each year if a percentage strategy was specified above or a range of the maximum number of breaks allowed if a number-of-breaks strategy was selected.

Possible prompt:

```
WHAT RANGE OF PERCENTAGES OF 8-, 12-, AND
16- TO 24-IN. MAINS WOULD YOU LIKE TO TEST?
ENTER A LOWER LIMIT, AN UPPER LIMIT, AND
A SKIP FACTOR IN ONE TEN THOUSANDTHS FOR
EACH DIAMETER GROUP.

FOR EXAMPLE: IF YOU WANT TO TEST A
STRATEGY WHICH REPLACES 1/1000 UP TO
1/100 OF EACH DIAMETER PIPE BY 1/1000
INCREMENTS OF EACH DIAMETER YOU WOULD ENTER:

LOWER LIMIT FOR 8-, 12-, and 16- TO 24-IN. = 10
UPPER LIMIT FOR 8-, 12-, and 16- TO 24-IN. = 100
SKIP FACTOR FOR 8-, 12-, and 16- TO 24-IN. = 10

ENTER LOWER LIMIT FOR 8-IN. MAINS
ENTER LOWER LIMIT FOR 12-IN. MAINS
ENTER LOWER LIMIT FOR 16- TO 24-IN. MAINS
ENTER UPPER LIMIT FOR 8-IN. MAINS
ENTER UPPER LIMIT FOR 12-IN. MAINS
ENTER UPPER LIMIT FOR 16- TO 24-IN. MAINS
ENTER SKIP FACTOR FOR 8-IN. MAINS
ENTER SKIP FACTOR FOR 12-IN. MAINS
ENTER SKIP FACTOR FOR 16- TO 24-IN. MAINS
```

Permissible responses: 1.0 - 10,000.0

Explanation:

If the percentage strategy was specified and different strategies were to be applied to different diameter groups, this prompt would appear. The program lets intervals as small as a one ten-thousandth of the system to be replaced each year.

Example: If it was desired to test replacing 0.001, 0.002, 0.003, 0.004, and 0.005 of the system each year for 8-in. mains, the user would enter 10 when asked to 'ENTER THE LOWER LIMIT FOR 8-IN. MAINS,' 50 when asked to 'ENTER THE UPPER LIMIT FOR 8-IN. MAINS,' and 10 when asked to 'ENTER THE SKIP FACTOR FOR 8-IN. MAINS.' The program will then go into a loop and replace 10/10,000, 20/10,000, 30/10,000, 40/10,000, and 50/10,000 of the 8" mains per year. Similarly, the

12-in. and 16- to 24-in.-diam groups are treated in the same manner and the same prompts are used.

Note: If the user wished not to test diameters separately, only one lower limit, one upper limit, and one skip factor would be asked for. These values would be applied to every diameter group (except 6-in. mains). If only one percentage is being tested for a diameter group, then the lower and upper limits should be the same (i.e. the desired percentage) and the skip factor should be 1.0. The difference between the upper and lower bounds must be a multiple of the skip factor.

Possible Prompt:

```
WHAT IS RANGE OF MAXIMUM NUMBER OF BREAKS WHICH YOU WOULD LIKE TO
TEST?

CHOICES ARE 1-5 WITH 5 REPRESENTING A DO-NOTHING SITUATION

ENTER A LOWER AND UPPER LIMIT
EXAMPLE #1:  IF YOU WANT TO TEST ALL 5 STRATEGIES YOU WOULD ENTER
LOWER LIMIT = 1
UPPER LIMIT = 5

FOR THE 8-, 12-, AND 16- TO 24-IN. DIAMETER GROUPS

ENTER LOWER LIMIT FOR 8-IN. DIAMETER GROUP
ENTER LOWER LIMIT FOR 12-IN. DIAMETER GROUP
ENTER LOWER LIMIT FOR 16- TO 24-IN. DIAMETER GROUP
ENTER UPPER LIMIT FOR 8-IN. DIAMETER GROUP
ENTER UPPER LIMIT FOR 12-IN. DIAMETER GROUP
ENTER UPPER LIMIT FOR 16- TO 24-IN. DIAMETER GROUP
```

Permissible responses: 1 - 5 (only integers)

Explanation:

If a number-of-breaks strategy was selected and different diameter groups were to be addressed with different strategies this prompt would appear. The skip factor is automatically set to 1. If all diameter groups were to be addressed with the same number-of-breaks strategy, the user would only be prompted for one lower limit and one upper limit. If one-or-more break, two-or-more break, three-or-more break, four-or-more break, and the do-nothing strategies are to be tested for the case of all diameters considered together, a 1 would be entered for the lower limit and a 5 for the upper limit.

If different diameters were to be tested separately, the user would have to enter a lower and upper limit for each diameter group.

Example: If it was desired to test the one-or-more break, two-or-more break, and three-or-more break strategies for the 8-in. mains group but only a one-or-more strategy for the 12-in. and 16- to 24-in. groups, then a lower limit of 1 would be entered for all three diameter groups and upper limits of 3 for the 8-in. groups and 1 for the 12-in. and 16- to 24-in. groups would be entered.

Note: If the user wished not to apply different strategies to different diameters, then the one-or-more, two-or-more, three-or-more, four-or-more, and do-nothing strategies would be applied to all diameters equally. In this case no additional prompts will be displayed.

Prompt: WHAT FRACTION OF EACH AGE GROUP WOULD YOU LIKE TO REPLACE?
(ENTER 0.0 IF ALL AGE GROUPS ARE TO BE TESTED EQUALLY)

ENTER FRACTION OF PRE-1929 MAINS TO BE REPLACED
ENTER FRACTION OF 1930-1969 MAINS TO BE REPLACED
ENTER FRACTION OF THE POST-1970 MAINS TO BE REPLACED

Permissible responses: 0 - 1.0 (for each of the three questions)

Explanation:

A fraction of each age group to be replaced must be entered. If the user is not interested in the effect of the age of pipes, he should enter 0.0 to each of the questions. If the user is interested in doing an age study, any fraction between 0.0 and 1.0 can be entered for each of the three age groups. This fraction will be multiplied by the length of mains to be replaced and reduce that number (if the fraction is greater than 0.0).

Prompt: WHAT RANGE OF DISCOUNT RATES WOULD
YOU LIKE TO TEST? ENTER A LOWER LIMIT, AN UPPER LIMIT, AND A SKIP
FACTOR IN ONE ONE-HUNDREDTHS.
FOR EXAMPLE: TO TEST DISCOUNT RATES OF 2%, 4%,
and 6%, YOU WOULD ENTER
LOWER LIMIT = 2
UPPER LIMIT = 6
SKIP FACTOR = 2

Permissible responses: 1 - 99 (The difference between the upper and lower bounds must be a multiple of the skip factor)

Explanation:

The user is being asked for a range of discount rates to test.

Example: If only one discount rate of 5% is to be tested, the user would enter

a 5 for the lower limit, a 5 for the .r limit and a 1 for the skip factor.

Prompt:
```
WHAT RANGE OF INDIRECT COST FACTORS WOULD YOU
LIKE TO TEST?  FOR EXAMPLE:  TO TEST ICF'S OF 1 AND 3 (0 AND 200%)
YOU WOULD ENTER
LOWER LIMIT = 1
UPPER LIMIT = 3
SKIP FACTOR = 1
ENTER LOWER LIMIT
ENTER UPPER LIMIT
ENTER SKIP FACTOR
```

Permissible responses: 1 - 10 (The difference between the upper and lower bounds must be a multiple of the skip factor)

Explanation:

The user is being asked for a range of indirect cost factors to test.

Example: If it was desired to test indirect cost factors of 2, 3, and 4, then 2 would be the lower limit, 4 would be the upper limit, and 1 would be the skip factor.

Prompt: HOW MANY YEARS DO YOU WANT TO SIMULATE?

Permissible responses: 1 - 50 (integers only)

Prompt:
```
WHICH PRINTOUT OPTION WOULD YOU LIKE?
1 -- ONLY RESULT SENT TO SCREEN
2 -- SUMMARY OUTPUT TO FILE SUMTABLE.DAT
     (SELECT THIS OPTION WHEN APPLYING DIFFERENT STRATEGIES TO
     DIFFERENT DIAMETER GROUPS BECAUSE A LARGE QUANTITY OF OUTPUT
     WILL BE GENERATED)
3 -- OUTPUT TO FILE PIPEOUT.DAT
ENTER CHOICE
```

Permissible responses: 1, 2, or 3

Explanation:

The user has the choice of three output options. Option 1 has the present value of cost of the strategy sent to the screen. Option 2 sends a summary table of costs and strategies to the file sumtable.dat. Since applying different strategies to different diameter groups creates considerable output, it is suggested that this option be chosen when applying different strategies to different diameter groups. It is not required, however, and if only a few runs are to be done, the last output option can be specified.

Option 3 sends the complete output (identical to that shown for the single run version of the program) for each iteration to the file pipeout.dat. If 100 runs are made, there will be 100 versions of the file pipeout.dat in the directory. Even though the output only takes up two pages, multiple runs can use many pages and use up available storage space.

Possible prompt: ENTER ANNUAL BUDGET FOR (borough)

Permissible responses: 1 - 1e12

Explanation:

This prompt will appear only once if a single borough is being tested or will appear five times if all boroughs are being tested. When it appears, the name of the pertinent borough will be specified. The budget to be entered is the yearly amount which will be spent on replacement in the borough of interest.

Note: As in the single run version, if the budget constraint is not desired, an arbitrarily large budget should be entered.