MIDWEST RESEARCH INSTITUTE

REPORT

OCCURRENCE, ECONOMIC IMPLICATIONS, AND HEALTH EFFECTS
ASSOCIATED WITH AGGRESSIVE WATERS IN
PUBLIC WATER SUPPLY SYSTEMS

FINAL REPORT

MRI Project No. 4552-L

For

A/C Pipe Producers Association
1600 Wilson Boulevard, Suite 1308
Arlington, Virginia 22209

Attn: John F. Welch

August 1979

MIDWEST RESEARCH INSTITUTE 425 VOLKER BOULEVARD, KANSAS CITY, MISSOURI 64110 • 816 753-7600

OCCURRENCE, ECONOMIC IMPLICATIONS, AND HEALTH EFFECTS ASSOCIATED WITH AGGRESSIVE WATERS IN PUBLIC WATER SUPPLY SYSTEMS

by

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PREFACE

This report is submitted in fulfillment of a contract with A/C Pipe Producers Association for the study of the "Economic Implications and Health Effects Associated with Aggressive Waters." The report describes a survey of municipal water supply systems and the analysis of the results obtained from the survey, and presents a discussion of the health effects associated with aggressive waters.

This report has been written by Dr. Michael J. Davis and Dr. Betty LaRue Herndon, who prepared Chapter 5 on the health effects of corrosive waters. Project leaders during the course of the project were Dr. Davis and Mr. E. Patrick Shea. Substantial input to the study has also been provided by Mr. Michael K. Snyder.

In addition to those mentioned above, numerous others have contributed much to the report. Mr. Richard O. Welch provided suggestions and counsel on economic considerations throughout the course of the study. Mr. Kenneth Walker carried out the literature search used to construct the bibliography presented in the report as Appendix IV. Mr. Arthur Tippit researched the cost information presented in Appendix II.

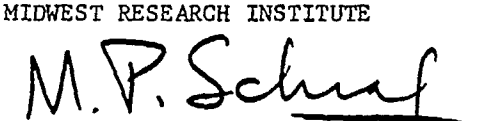
Dr. Thurston Larson, who was a consultant to the study, provided many useful suggestions concerning the survey design and the analysis of the results.

Finally, credit must be given to the many utilities who provided the information used in this study, and to the state and federal agencies and consulting firms who supplied us with much necessary additional information.

Questions concerning this report should be directed to the authors or to Mr. Maury Schrag, Deputy Director of the Environmental and Materials Sciences Division.

Approved for:

MIDWEST RESEARCH INSTITUTE



M. P. Schrag, Deputy Director
Environmental and Materials
Sciences Division

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EXECUTIVE SUMMARY

A study has been carried out to examine the extent to which consumers are exposed to drinking water of a corrosive or aggressive nature, and to estimate the economic impact of these waters on the utilities distributing them. An estimate has also been made of the national cost of stabilizing waters found to be aggressive for utilities serving 50,000 or more consumers. The potential health effects of aggressive waters themselves (particularly soft water) and the toxicants which may be released from materials contacted by corrosive waters is also discussed.

The present study was based on a survey of public water supply systems. All utilities serving 50,000 or more population which could be identified were contacted. Similarly, a sample of the utilities in the group serving between 10,000 and 50,000 people was also contacted. These utilities were requested to provide information on their size, the character of the water they distributed, treatment processes used, and nature of distribution system, as well as various cost data. In all, over 1,000 utilities were contacted, roughly 500 in each size group.

Responses were received from 47.4% (255 utilities) of the utilities contacted in the larger size group. The response rate was 10.5% (54 utilities) for the smaller utilities. The difference in response rate is partially due to the fact that larger utilities tend to provide a higher response rate, but it is also largely the result of a thorough follow-up of the survey in the larger size group.

Because of the poor response rate and the relatively low quality of the responses received, an analysis of the results from the smaller utilities was not made. All results described here refer to the 50,000 or more served size group.

In addition to the responses obtained directly from utilities, secondary sources of information--primarily state agencies--were used to provide data on the utilities. Such secondary sources yielded information on an additional 162 utilities (30.1% of the size group). The utilities that were not characterized are generally smaller than average for the group. The utilities for which information was obtained serve over 93% of the population in the utility size group studied.

Using the information obtained on the quality of water distributed by the utilities, the portion of the population exposed to waters of varying degrees of aggressiveness was determined. About 70% of the population studied is exposed to water which has a negative Langlier Saturation Index (LSI) when it enters the distribution system. This indicates that the water is at least mildly aggressive. About 30% of the population is exposed to

water with an LSI below -1.0 before dist 'bution; about 10% drinks water that has an LSI less than -2.0 when it enters the distribution system. This water can be considered to be highly aggressive.

Among those utilities studied who distribute aggressive water (LSI less than -0.5), about 26% report losses due to internal corrosion. For those utilities whose water has an LSI above -0.5, 13% report such losses. For those utilities who distribute aggressive water and experience losses due to internal corrosion (31 utilities), the average annual per capita cost of such losses is estimated at $1.19. For those experiencing losses but which have nonaggressive water (16 utilities), the annual per capita cost of the losses is $0.58. These cost estimates are based on pipe replacement information and reported losses to internal corrosion provided by the utilities.

A substantial fraction of the losses to internal corrosion experienced by utilities with aggressive water should be avoidable if the water were properly stabilized chemically before it entered the distribution system. An estimate was made of the stabilization cost for each utility determined to be distributing aggressive water (as determined from the survey and secondary sources). Such stabilization was carried out using lime and carbon dioxide.

The costs for the individual utilities were combined to give a national estimate of the cost of stabilization of aggressive waters for utilities of the size group studied. For the 177 utilities involved (serving 52.6 million population) the annual cost of stabilization is estimated at $7.5 million or $0.14 per capita. This estimate assumes a minimum level of stabilization. A very conservative approach to stabilization could triple the costs, giving an annual per capita cost of $0.42. The influence of the utilities not accounted for in the analysis is such that their addition should not increase the above per capita costs more than $0.01 even under what are considered to be conservative assumptions. These costs have not included transportation costs for chemicals because of the difficulty involved in estimating haul distances for the many utilities studied. Assuming a rather arbitrary $20.00/ton (300-mile haul distance) as a transportation cost, the annual per capita cost of the two stabilization approaches mentioned would increase to $0.18 and $0.57.

For utilities experiencing losses due to internal corrosion and which have aggressive water, the average ratio of the costs that could be avoided by chemically stabilizing the water to the cost of stabilization is estimated to be in the range of 3.8 to 4.8. Note that this is an average ratio--the value can vary substantially from utility to utility within the group.

Four utilities experiencing losses to internal corrosion were considered as case studies. These utilities were selected to provide a range of utility sizes, locations, and types of water distributed. Three of the four utilities would probably benefit from a stabilization program (the fourth already has one). However, three and possibly four of these utilities also have a problem at least in part because of some of the materials used in their distribution systems--poorly protected steel and cast iron.

There are several useful programs of research which might be carried out to further extend the above results. The first is simply a refinement of the present study which would allow some data gaps to be filled and which would allow improved or alternative stabilization costs to be determined. The second program would involve a very careful sample survey of utilities in this size group. The survey would be based on visiting and interviewing the selected utilities. Such an approach should overcome some of the quality control problems associated with a mailed survey. The third program is intended to go beyond the limits of information available to most utilities by actually carrying out experimental analyses for a small number of utilities. A study of this type should clarify the extent to which utilities are actually aware of their internal corrosion problems.

The health effects of corrosive water have been reviewed. The major emphasis is on the cellular toxicity of trace elements as they exist in corrosive water, particularly as they differ from the elements found in normal high mineral water. These elements include beryllium, cadmium, calcium, copper, lead, magnesium, manganese, vanadium, and zinc. Current scientific theories on the health effects of the major corrosive water constituents or contaminants are reviewed. Although circumstantial evidence is strong, human epidemiological studies have not conclusively shown that the trace elements leached from the environment by corrosive (aggressive) water have deleterious cardiovascular effects.

Since corrosive water also dissolves the matrix of asbestos-cement pipe and frees asbestos fibers, the effects of ingested asbestos in man and experimental animals were also reviewed. Although the exposure route differs and, therefore, possible the effect, the review also covers the reports of the high incidence of cancers in lung and abdominal tissue in individuals who inhale asbestos fibers.

Data on the human effects of asbestos fibers swallowed in potable water are still being collected. Animals, orally administered very high doses of asbestos, have no shortened life spans, but have developed tumors.

What is known concerning the health effects of corrosive waters can be summarized as follows: (a) mechanisms exist by which cardiovascular damage could occur as a result of trace element intake; (b) corrosive water contains many metals, leached from the environment, at least four of which

have been shown to be involved in facets of cardiovascular disease in experimental animals; and (c) epidemiological studies worldwide have found geographical correlation between corrosive water areas and cardiovascular disease.

Conclusions

1. Rather aggressive water is commonly distributed by municipal water supply systems. The portion of the U.S. population (served by utilities with 50,000 or more population served) exposed to water with an LSI less than -2.0, when it enters the distribution system, is in the range of 10.0 to 11.9% (11.3 to 13.4 million people). The portion of the population exposed to water with an LSI less than -1.0 before distribution is in the range 28.5 to 32.3% (32.3 to 36.5 million people). The population in the first group can be considered to be exposed to water that is highly aggressive when it enters the distribution system.

2. The portion of the population exposed to highly aggressive waters is of the greatest interest and concern, but the population (and number of utilities in the 50,000 and above size group) exposed to waters of varying aggressiveness is also of interest. It has been determined that approximately 70% of the utilities in the 50,000 and above size group distribute water that can be considered at least mildly aggressive (LSI less than 0.0). These utilities serve about 70% of the population in this size group.

3. Approximately 26% of the utilities studied that distribute aggressive water (LSI less than -0.5) report losses due to internal corrosion. Among those who distribute nonaggressive water (LSI greater than -0.5), about 13% report losses.

4. Based on survey results, a best estimate of average annual costs of internal corrosion to all the utilities studied is $0.91 per capita for all those utilities reporting losses (47 utilities), and $1.19 per capita for those utilities distributing water with an LSI less than -0.5 and which report losses (31 utilities).

5. For those utilities reporting losses due to internal corrosion, the average annual cost of chemically stabilizing the water is estimated at $0.20 per capita, neglecting chemical transportation costs.

6. The average ratio of benefits (internal corrosion prevented by stabilization) to costs (cost of chemical stabilization) is in the range of 3.8 to 4.8 for all those utilities reporting internal corrosion losses and who distribute aggressive water in the size group studied (50,000 population and above served).

7. The annual national cost of chemical stabilization of aggressive waters for all utilities in the size group studied is estimated to be $7,530,000, or $0.14 per capita. The total population involved is approximately 52,600,000. (These estimates do not include chemical transportation costs, which could increase total costs by as much as 20 to 30%.)

CHAPTER 1

INTRODUCTION

1.1 Chemistry of Corrosive Waters

The aggressiveness (or corrosiveness) of water being distributed by municipal water supply systems is of importance for two reasons: (a) because of the possibility that the water may produce a deterioration of the distribution system and (b) because of the possibility that there may be adverse health impacts on those drinking the water. At present, it is not possible to fully quantify the degree to which distribution systems and the health of consumers are impacted by corrosive water. This study describes the results of a research program which has been carried out with the goals of (a) assessing the extent of aggressive water in municipal water supplies, (b) estimating the economic impact of such water on distribution systems, and (c) discussing the potential for adverse health effects associated with corrosive waters.

Aggressive waters can destroy the materials used to construct the pipe which transports the water. Such an attack has several impacts: the pipe may be damaged structurally, the carrying capacity of the pipe may be reduced, and the materials used in the construction of the pipe may be released into the water and ingested by consumers. All of these factors are potential causes for concern. Stabilization of the water and proper materials selection in the distribution system can do much to eliminate the problems of aggressive waters.

Corrosion* is usually thought of as a problem involving only metals. However, corrosion of nonmetallic solids can also occur. Such an attack is nonelectrochemical and depends only upon the extent to which the water is saturated with the material in question. In the case of a nonmetallic solid, it is simply dissolved by the water.

For metals, the process is usually electrochemical. The corrosion may be thought of as occurring in many corrosion cells consisting of anodes and cathodes. The anodes and cathodes are connected by paths through the water and (usually) through the corroding metal. These paths form a complete electrical circuit. Oxidation occurs at the anode and reduction occurs at the cathode. The anodic and cathodic areas may be very close together (i.e., a few molecules apart). In this case uniform corrosion occurs. If the electrodes (anode and cathode) are farther apart, pitting may occur, possibly along with tuberculation. Corrosion products may form

* For more details, see Larson (1971, 1975) or Camp (1963).

on the surface of the pipe, producing a protective layer that tends to stabilize the pipe surface. These products may be oxides, carbonates, or hydrated oxides of the metal. These substances may also form nodules (tuberculation) on the interior pipe surface and in so doing decrease the flow rate in the pipe.

Concrete, cement mortar, and asbestos-cement will also corrode in water. The corrosion of these materials is caused by the leaching of cement into the water. With time, leaching will occur from the interior of the pipe as material that is near the surface is dissolved. This leaching will occur at a decreasing rate over a long period.

To protect against corrosion of pipe interiors, a barrier may be set up between pipe and water. Commonly, cement-mortar linings, bituminous seal coats, or other organic coatings are used for this purpose. Such protective coatings may be mechanically applied (e.g., cement linings or coatings) or deposited chemically in situ (e.g., silicates or polyphosphates). In the latter category, calcium carbonate ($CaCO_3$) deposition may also be used for protection against corrosion. Merrill and Sanks (1977, 1978) have discussed corrosion control using $CaCO_3$ films.

The degree of corrosion in water distribution systems is a function of the character of the water, but it is also a function of the materials used in the distribution system, and of flow conditions. The focus of this study was on the impact of aggressive waters on distribution systems and how these waters may be stabilized to reduce corrosion. Water quality aspects are therefore emphasized. That does not mean that the nature of the distribution system is unimportant.

1.2 Corrosion Indices

A number of indices have been developed to estimate the corrosion potential of water. One of the first and the most widely used is the saturation index developed by Langlier (1936). The LSI expresses the potential of a water to either dissolve or precipitate $CaCO_3$. The index is defined as the difference between the measured pH of the water and the pH at which $CaCO_3$ would be at saturation concentration:

$$LSI = pH_{measured} - pH_{saturation}$$

At pH values of interest in water supply systems, a positive value of LSI indicates over-saturation and a negative value indicates an under-saturation of $CaCO_3$. A value of zero indicates equilibrium.

For the purpose this discussion, a sufficiently accurate expression for saturation index has been given by Larson and Buswell (1942):

$$pH_{saturation} = \log\left[\frac{K_s}{K_2}\right] - \log\,[Ca^{++}] - \log[Alk] + 9.30 + \frac{2.5\sqrt{\mu}}{1 + 5.3\sqrt{\mu} + 5.5}$$

where K_s = solubility constant for $CaCO_3$

K_2 = second ionization constant for H_2CO_3

$[Ca^{++}]$ = the calcium concentration in mg/liter

$[Alk]$ = the alkalinity in mg/liter as $CaCO_3$

μ = ionic strength

This expression is valid for $pH_{saturation}$ between about 6.5 and 9.5. Positive values of LSI indicate a tendency for the water to deposit a protective $CaCO_3$ layer on the pipe, and hence impede corrosion. Negative values indicate a tendency to dissolve $CaCO_3$ from the pipe's interior and thus a tendency to be aggressive to the pipe. The index shows only directional tendency and is not quantitative.

If one assumes typical values for TDS and temperature, LSI may be rewritten as:

$$LSI = pH_{measured} + \log\left([Ca^{++}]\ [Alk]\right) + \text{Constant}$$

$[Ca^{++}]$ may be expressed as calcium hardness as $CaCO_3$. If this is done, the value of the constant for reasonably typical values of temperature and TDS is 12.0. Subtracting the constant from the above expression gives the Aggressiveness Index (AI).

$$AI = pH_{measured} + \log\,(AH)$$

where: A = alkalinity in mg/liter as $CaCO_3$

H = calcium hardness in mg/liter as $CaCO_3$

This index is therefore seen to be a simplified version of the LSI. As will be shown in this study, for practical assessment purposes, the two indices can be used nearly interchangeably. However, if minor adjustments due to temperature and dissolved solids are of concern, LSI should be used.

For AI, the aggressiveness of a water may be placed in three categories (AWWA, Specification C400, 1977):

1.	Nonaggressive	$AI \geq 12.0$
2.	Moderately aggressive	$10.0 \leq AI < 12$
3.	Highly aggressive	$AI < 10$

These values correspond roughly to LSI values of above 0.0, between -2.0 and 0.0, and below -2.0, respectively.

A third index was developed by Ryznar (1944). It makes use of the same parameters as does the LSI, but attempts to account for the effect of pH, not just the difference between measured and saturation pH. The Ryznar Stability Index (RSI) is given by:

$$RSI = 2\ pH_{saturation} - pH_{measured}$$

Values above 7.0 indicate a corrosive water while those below that value indicate scale forming tendencies. The index seems most useful in comparing waters of different composition.

Other indices have been suggested (see Dye and Tupeken (1971) for a short discussion of some additional indices and experimental tests related to determining the aggressiveness of a water).

These three indices were considered in the present study. They are certainly not infallible guides to predicting corrosion in a water distribution system, as later discussion will demonstrate. However, the discussion will also show that most utilities reporting losses due to internal corrosion have aggressive water, as determined by these indices. However, the converse is not true, as most utilities with "theoretically" aggressive water did not report losses due to internal corrosion. This finding suggests (a) that factors other than the degree of aggressiveness predicted by these indices are important and (b) that water utilities may not be aware of the nature and extent of losses due to internal corrosion.

It is likely that the degree of destruction of water supply distribution systems is greater than that reported or recognized by the utilities themselves. There probably are many situations in which other factors are also involved. For example, a pipe may be corroded both externally and internally. In this case, should the utility assign the loss to internal or external causes? Also, the age of the pipe being replaced and the treatment history of the system have an effect on pipe replacement for which it is difficult to account. Therefore, while an index cannot be expected to be a perfect guide to predicting where corrosion problems will occur, it should point out potential problem areas, and should be even more useful if health effect considerations are included, since considerable loss of material can occur without pipe failure.

Due to the economic importance of corrosion, the development of a reliable "universal index" would provide a very valuable tool. Such an index has been the desire of many investigators since Langlier's early efforts in the 1930s. However, the problem is a formidable one because of the many factors involved. These include: pH, temperature, calcium concentration, alkalinity, heat transfer rate, dissolved oxygen and CO_2 concentrations, metallurgical conditions in the distribution system, the electrochemical reactions involved, the electrolytic cells caused by the presence of dissimilar materials, flow velocity, contact time, etc. The problem is further compounded by the varying composition of distribution system materials, and the corrosion chemistries inherent to each. It is difficult to conceive of a single index which would accurately and simultaneously predict, for example, corrosive attack on metallic and cementitious piping materials. Since the system is so complex, the likelihood that a reliable "universal index" will be developed is not large. To expect such an index to be even generally useful in predicting the release of potentially toxic substances from distribution system materials seems beyond the realm of practicality at this time.

1.3 Objectives of This Study

The present study was undertaken to accomplish three objectives:

1. To determine the U.S. population exposed to waters of varying degrees of aggressiveness.

2. To estimate the economic impact of aggressive waters on municipal water supply systems, and also, to estimate the cost of chemically stabilizing aggressive waters to minimize such impact.

3. To assess the potential health effects of aggressive waters themselves (particularly soft water), as well as the health effects associated with toxicants released from materials in contact with aggressive waters.

1.4 Approach Used in This Study

There are on the order of 35,000 community water supply systems in the United States. These range in size from those serving tens of individuals to those with millions of consumers. However, over 85% of the population served by utilities is served by utilities having 10,000 or more consumers. Similarly, about 64% of the population is served by utilities with 50,000 or more consumers. Over 92% of the utilities serve less than 10,000 people. Therefore, by focusing on the larger utilities, the number to be studied is greatly reduced and a very substantial fraction of the population is still involved. Small utilities also are likely to be less prepared to provide information than larger utilities.

The study, therefore, was limited to the larger utilities, relatively speaking. It was our judgment that a utility size of 50,000 or more consumers would be necessary if high quality data, as well as a high rate of return from a survey, were to be expected. The results of the study have borne out this judgment.

The data used in this study were collected by mailed questionnaires. These questionnaires were designed to obtain information on the size of the utility, the quality of its water, the treatment processes used, the nature of the utility's distribution system, its operating expenses, and an estimate of the impact of water related corrosion on the utility's system.

Two broad size groups of utilitites were considered: those serving between 10,000 and 50,000 people and those serving 50,000 and above. The different number of utilitites involved in the two groups required that they be treated in different ways. There are about 500 utilities in the 50,000 and above group, and over 2,000 utilities serving between 10,000 and 50,000 population. Resources allowed about 1,000 utilities to be contacted. It was decided to survey all utilities serving 50,000 or more and to contact a random sample in the 10,000 to 50,000 size group for exploratory reference purposes. The sample size chosen was such that the total number of utilities studied was about 1,000.

Utilities were identified using a list supplied by the U.S. Environmental Protection Agency's Office of Drinking Water. This list had substantial errors in it and a careful effort was made to screen out inappropriate entries and to correct and supplement the list as needed.

Chapter 2 describes the survey in detail and discusses the nature of the response in the two size groups.

The returned questionnaires were processed to determine the distribution of population by aggressiveness of water supplied. The surveys were also analyzed to estimate the economic impact of aggressive waters on public water supply systems. The details of the analysis and the results

obtained are discussed in Chapter 3. Chapter 4 presents results for four utilities which are considered case studies, demonstrating the range of internal corrosion problems experienced by utilities.

In addition to the data obtained from responses to the survey, supplementary sources of data were also used. Such information allowed nearly all utilities serving 50,000 or more people to be characterized in terms of the quality of water distributed.

CHAPTER 2

AGGRESSIVE WATER SURVEY

2.1 Background

To date the actual extent of aggressive waters in the United States has not been firmly established. A common statement is that half the water distributed in the United States is aggressive. Generally speaking, there has been little effort to quantify nationally the number of people exposed to waters of varying degrees of aggressiveness, and even less effort to estimate economic losses associated with aggressive water.

Probably the best relevant study to date has been that by Millette et al. (1979). Their research was conducted in conjunction with a National Center for Health Statistics (NCHS) study to investigate the relationships between trace metals in drinking water and cardiovascular disease. NCHS contracted with the Bureau of Census to randomly select a representative sample of individuals throughout the United States. The Bureau selected 35 geographically distributed areas, at random. Within each area utilities were randomly selected. The total sample contained 130 utilities serving over 40 million people. Based on their sample, Millette et al. found the following distribution of utilities by AI. Their analysis also showed that AI gives results equivalent to LSI for determining if a water is aggressive.

Highly aggressive ($AI < 10$)	16.5% of utilities
Moderately aggressive ($10 \leq AI < 12$)	52% of utilities
Nonaggressive ($AI \geq 12$)	31.5% of utilities

No results were presented on the distribution of population served by degree of aggressiveness. (Population and utilities are distributed somewhat differently, as will be shown in Chapter 3.) It will be shown in Chapter 3 that these results agree very closely with those obtained during the present study.

Other studies have been considerably less useful in establishing national exposure to aggressive waters. Most references refer to specific utilities or in a nonquantified fashion to a geographical region. Such sources establish the occurrence of substantial problems in large and small utilities (e.g., the Seattle Corrosion Study by Kennedy Engineers (1976, 1978) or reports of problems in Philadelphia by Radziul and Jackson (1965) and Radziul et al. (1965, 1967).

Hudson and Gilcreas (1976) have made estimates of national costs due to internal corrosion losses. Their estimates make use of relatively

little firm data and in so doing indicate the lack of information available. The data base used by Hudson and Gilcreas for estimating extent of aggressiveness was a U.S. Geological Survey study of the 100 largest cities in the United States (Durfor and Becker, 1964).

With the exception of the recent work by Millette et al. (1979), there appears to have been no serious attempt at quantifying the degree of aggressiveness nationally. That study did not address the problem of how population (rather than utilities) is distributed by degree of aggressiveness. There appears to have been no detailed attempt to appraise the economic impact of aggressive waters on a national basis. The present study was designed to supply relevant, national information in these areas.

2.2 Utilities Studied

Two groups of utilities were studied: those serving between 10,000 and 50,000 people and those serving 50,000 and above. These utilities were identified using a computerized list supplied by the U.S. Environmental Protection Agency (EPA), Office of Drinking Water. Based on EPA data, there are 2,165 utilities in the 10,000 to 50,000 group and 587 utilities in the above 50,000 group. If one goes below 10,000 population served, the number of utilities increases very rapidly. For example, there are 1,820 utilities in the 5,000 to 10,000 size group alone. It seemed logical that the smaller the utility, the less are the resources available for responding to requests for information. Ten thousand population served was picked as a rather arbitrary, but practical, cut-off point. Since the resources available did not allow contacting all utilities serving above 10,000 people and since the response of the larger utilities was deemed more important, two different approaches were used for the two groups studied.

Resources allowed about 1,000 utilities to be contacted, not all of them more than once. It was decided to contact all utilities serving above 50,000 population which could be identified. A mailing to each of these utilities was made. If no response was obtained to the first mailing, it was followed by a second mailing. Next, utilities in selected areas were contacted by telephone if no responses were received from the second mailing. Finally, an effort was made to obtain data from the states in which the utilities are located, if no input was received directly from the utility. Such an overall approach was expensive and time consuming, but led to a good response rate.

For the 10,000 to 50,000 group a random sample of utilities was selected. The sample was selected separately from each state, with the states in which soft water is prevalent having twice the relative sample size as the hard-water states. Only a single mailing was used and there

was no follow-up on the utilities. As might be expected, the response was relatively poor.

For both size groups only the 48 conterminous states were included.

The EPA mailing list used contained substantial errors. Prior to sample selection in the 10,000 to 50,000 size group, a careful effort was made to eliminate incorrect entries and redundancies. No additional data sources were used. For the 50,000 and above group, the list was examined very carefully and similar errors were eliminated. In addition, the list was supplemented by other sources. It is expected that virtually all of the largest utilities have been identified. However, there is considerable chance that numerous smaller (e.g., near 50,000 population) utilities may have been omitted. This can occur for a number of reasons: errors in EPA's list; recent growth of utilities into the 50,000 and above group; and increased difficulty of identifying the smaller utilities.

In all, 538 utilities (somewhat less than the number on the EPA list) were identified in the 50,000 and above group. Results describing these utilities and their response will be presented below.

Table 2-1 lists the number of utilities identified and the size of the survey mailing by state for the 10,000 to 50,000 size group. Surveys were mailed to 38% of the utilities in soft-water states and 19% of the utilities in hard-water areas. These values were chosen to give a total of about 500 utilities surveyed in the size group and to give twice the emphasis to soft-water areas as compared with hard-water areas.

2.3 Survey Methodology

The utilities were asked to complete the survey form shown in Figure 2-1. The questionnaire asked for information in several different categories and formed the basis for the analysis conducted in this study.

TABLE 2-1

SAMPLE SELECTION FOR THE
10,000-50,000 SIZE GROUP

State	Number of Utilities Identified	Number of Utilities to Whom Surveys Were Mailed
AL	36	14
AZ	15	3
AR	21	8
CA	234	44
CO	23	4
CT	36	14
DE	2	1
FL	110	21
GA	45	17
ID	11	2
IL	145	27
IN	51	10
IA	25	5
KS	25	5
KY	28	5
LA	42	8
ME	19	7
MD	17	6
MA	90	34
MI	86	16
MN	51	10
MS	28	11
MO	39	7
MI	6	1
NE	14	3
NV	4	1
NH	14	5
NJ	97	18
NM	15	3
NY	120	23
NC	54	20
ND	5	1
OH	95	18
OK	33	6
OR	41	15
PA	127	24
RI	9	3
SC	41	15

TABLE 2-1 (concluded)

State	Number of Utilities Identified	Number of Utilities to Whom Surveys Were Mailed
SD	7	1
TN	48	9
TX	80	15
UT	19	4
VT	7	3
VA	35	13
WA	56	21
WV	11	2
WI	42	8
WY	6	1
Totals	2,165	512

SURVEY ON IMPACT OF AGGRESSIVE
WATERS ON MUNICIPAL WATER SUPPLY SYSTEMS

Please answer as many questions as possible; skip those which you are unable to answer or which you feel would involve the release of confidential information.

I. BACKGROUND INFORMATION

Name of Utility _____

Address: Street _____

City _____ State _____ Zip _____

Telephone _____

Period for which data are given (check): Calendar year 1977 [24] ☐ Other ☐

If "other" is checked, please specify period: _____

Source(s) of water supply (e.g., river (name), wells (number), etc.) _____

Volume of water consumed (MGD) [25] ☐☐☐☐.☐☐

Population served (thousands) [31] ☐☐☐☐.☐☐

Number of treatment plants operated [37] ☐☐

Length of distribution system (miles) [39] ☐☐☐☐

What are your annual costs due to water-related corrosion losses? [43] ☐☐☐☐☐☐☐☐

What are your annual costs for protection from water-related corrosion? [51] ☐☐☐☐☐☐☐☐

Name and title of person completing survey (optional) _____

II. CHARACTER OF RAW AND FINISHED WATER

Parameter	Raw Water (average values)	Finished Water (average values)
Alkalinity (mg/ℓ as $CaCO_3$)	[59] ☐☐☐☐	[63] ☐☐☐☐
Total Hardness (mg/ℓ as $CaCO_3$)	[67] ☐☐☐☐	[71] ☐☐☐☐
Total Dissolved Solids (mg/ℓ)	[75] ☐☐☐☐	[78] ☐☐☐☐
Calcium Concentration (mg/ℓ)	[10] ☐☐☐☐	[14] ☐☐☐☐
Magnesium Concentration (mg/ℓ)	[18] ☐☐☐☐	[22] ☐☐☐☐
pH	[26] ☐☐.☐	[29] ☐☐.☐
Temperature: Maximum (°F)	[32] ☐☐.☐	[35] ☐☐.☐
Minimum (°F)	[38] ☐☐.☐	[41] ☐☐.☐

Figure 2-1 - Survey Form Used

III. TREATMENT USED

Type of Treatment	Check Process(es) Used	Volume of Water Treated by This Process (MGD)	Year Installed
Sedimentation	44 ☐	45 ☐☐☐☐.☐☐	51 ☐☐☐☐
Filtration	55 ☐	56 ☐☐☐☐.☐☐	62 ☐☐☐☐
Activated Carbon	66 ☐	67 ☐☐☐☐.☐☐	73 ☐☐☐☐
Ion Exchange	3-6 ☐	7 ☐☐☐☐.☐☐	13 ☐☐☐☐
Lime-soda	17 ☐	18 ☐☐☐☐.☐☐	24 ☐☐☐☐
Dual Media	28 ☐	29 ☐☐☐☐.☐☐	35 ☐☐☐☐
Chlorination	39 ☐	40 ☐☐☐☐.☐☐	46 ☐☐☐☐
Other (please specify) _____	50 ☐	51 ☐☐☐☐.☐☐	57 ☐☐☐☐

Please estimate the quantity of each of the following chemicals used:
(Units: lb/million gallons treated)

Lime:	61 ☐☐☐☐.☐	Polyelectrolytes:	66 ☐☐☐☐.☐
Soda ash:	71 ☐☐☐☐.☐	Activated carbon:	76 ☐☐☐☐.☐
CO_2:	4-6 ☐☐☐☐.☐	Phosphates:	11 ☐☐☐☐.☐
Alum:	16 ☐☐☐☐.☐	Other (please specify): _____	21 ☐☐☐☐.☐

IV. NATURE OF INSTALLED PIPE

	Type of Pipe: Steel	Cast-Iron	Asbestos-Cement	Concrete	Plastic	Other (specify)
Portion of system which uses this material (%)	26 ☐☐☐	42 ☐☐☐	58 ☐☐☐	74 ☐☐☐	17 ☐☐☐	33 ☐☐☐
Typical diameter (in.)	29 ☐☐	45 ☐☐	61 ☐☐	77 ☐☐	20 ☐☐	36 ☐☐
First year installed	31 ☐☐☐☐	47 ☐☐☐☐	63 ☐☐☐☐	5-6 ☐☐☐☐	22 ☐☐☐☐	38 ☐☐☐☐
Amount of pipe of this type replaced annually, on average (miles)	35 ☐☐☐☐	51 ☐☐☐☐	67 ☐☐☐☐	10 ☐☐☐☐	26 ☐☐☐☐	42 ☐☐☐☐
Portion of replacement due only to internal corrosion (%)	39 ☐☐☐	55 ☐☐☐	71 ☐☐☐	14 ☐☐☐	30 ☐☐☐	46 ☐☐☐

V. COSTS

Please estimate the following treatment costs:

Operating Cost ($/year)	49	
Maintenance Cost ($/year)	57	
Capital Replacement Cost ($/year)	65	
Depreciation Cost ($/year)	73	

Please estimate the following costs for your distribution system:

Capital replacement cost ($/year)	6-6	
Operation and maintenance cost (labor and materials) ($/year)	14	
Depreciation cost ($/year)	22	

Please estimate the following:

Water-related corrosion costs for metering equipment ($/year)	30	
Water-related corrosion costs for storage facilities ($/year)	38	

Thank you for your cooperation in this survey. Please return this form to:

Midwest Research Institute
425 Volker Boulevard
Kansas City, Missouri 64110

in the enclosed, self-addressed envelope. Please add any comments or clarifications below or on the reverse side.

The areas for which information was requested were:

1. General identification of the utility;

2. Size of the utility;

3. Character of raw and finished water distributed;

4. Types of treatment used;

5. Nature of pipe installed and pipe replaced; and

6. Costs

   - Treatment costs
   - Distribution costs
   - Internal corrosion related costs

A cover letter explaining the purposes of the survey was sent with each questionnaire. For those utilities in the 50,000 and above group, an annual report was also requested. The annual reports were found to be very useful in supplementing the information provided on the questionnaire, particularly when the utility did not respond to most questions.

Sometime after the first questionnaire had been mailed, a second questionnaire was mailed to the nonrespondent utilities in the 50,000 and above served group. This second mailing roughly doubled the response rate. After a second waiting period, all nonresponding utilities in the 50,000 and above group in soft-water states were contacted by telephone. Many surveys were completed over the telephone and some utilities provided further data by mail. Finally, after the telephone survey was nearly complete, data were requested from states in an attempt to provide water quality information for the utilities which had provided no data.

The survey of the 10,000 to 50,000 size group was ended after the first mailing.

As a result of the response to the first mailing, several ambiguities in the survey form were discovered. These were corrected in the second mailing. The form shown in Figure 2-1 is the corrected version. The ambiguities involved the volume of water produced by the utility and the extent of internal corrosion. On the first survey, the question "Volume of Water Treated" was asked. Some of those utilities buying their water and not treating responded with an answer of "0," even though the cover letter requested that they complete the pertinent parts of the form even if they purchased their water. On the second mailing "Treated" was changed to "Consumed." An ambiguity concerning sources of corrosion was

eliminated by adding the modifier "Water-related" or "Internal" to all references to corrosion.

Due to the ambiguous wording on internal corrosion on the first questionnaire, a number of utilities experiencing external corrosion problems responded, indicating they had losses due to corrosion. All utilities which responded to the first mailing indicating they were experiencing corrosion losses were contacted again by telephone to clarify the nature of their corrosion problems.

2.4 Survey Results

Table 2-2 illustrates the response obtained from the 50,000 and above group based on the two mailings and the telephone follow-up. Table 2-2 shows results by state and by source, i.e., data obtained directly from the utility or from secondary sources. Overall, 538 utilities were identified. Two hundred fifty-five of these responded to the survey. Another 162 were characterized using state departments of health or other sources for information.* A 47% direct response was obtained; a total of 77.5% of all identified utilities was characterized at least in terms of quality of water distributed. Since most utilities not characterized have considerably less than the average population for the group, the total population included is much above 77.5%, actually 93.3% of the total population identified.

In an effort to estimate the total population in the size group, and to determine the influence of an incomplete response, the utilities not characterized (Column 6 of Table 2-2) were analyzed. The results are shown in Table 2-3. This table shows the population served by the missing utilities. It also shows that a substantial number of the "missing" utilities already had their population accounted for in the population served by one of the utilities characterized and, in that sense, were not really missed at all. (There is no double counting since the population given in Table 2-3 is only for utilities contributing additional population.) Table 2-4 shows an estimate of total population in the 50,000 and above group for those utilities identified.

The number of utilities given in Table 2-4 is different from the number given in Table 2-2 for two reasons: (a) as indicated in Table 2-3, a number of utilities effectively serve zero population because of double counting and (b) some of the utilities in the 538 identified actually serve populations less than 50,000. These were removed from the size group and are not included in the analysis for the group. Four hundred eighty-seven represents the best estimate of utilities (primary source only) serving above 50,000 population.

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* Secondary sources of data are given in Appendix V.

TABLE 2-2

SURVEY RESPONSE
(50,000 and Above Group)

(1)	(2)	(3)	(4)	(5)	(6)
State	Number of Utilities Identified	Responses: Positive	Responses: Negative/Incomplete	Utilities Characterized From Supplementary Sources	Utilities Not Characterized (2)-(3)-(5)
AL	9	3	-	5	1
AZ	6	4	-	1	1
AR	5	3	-	2	0
CA	78	22	8	4	52
CO	8	5	-	1	2
CT	10	3	-	6	1
DE	3	2	-	0	1
DC	1	1	-	0	0
FL	28	13	1	8	7
GA	12	8	-	3	1
ID	1	1	-	0	0
IL	27	12	-	6	9
IN	11	5	-	4	2
IA	7	4	-	3	0
KS	5	4	1	1	0
KY	6	1	1	4	1
LA	9	1	-	8	0
ME	1	1	-	0	0
MD	7	5	-	0	2
MA	21	16	-	4	1
MI	25	8	-	7	10
MN	6	3	-	3	0
MS	3	2	-	1	0
MO	9	4	-	5	0
MT	3	3	-	0	0
NE	2	2	-	0	0
NV	3	3	-	0	0
NH	1	1	-	0	0
NJ	22	6	-	15	1
NM	1	0	-	1	0
NY	38	10	-	23	5
NC	11	8	-	1	2
ND	3	1	-	0	2
OH	26	16	-	3	7
OK	4	1	-	3	0
OR	3	2	-	1	0

TABLE 2-2 (CONCLUDED)

(1) State	(2) Number of Utilities Identified	(3) Responses Positive	(4) Responses Negative/Incomplete	(5) Utilities Characterized From Supplementary Sources	(6) Utilities Not Characterized (2)-(3)-(5)
PA	31	18	2	6	7
RI	5	4	-	0	1
SC	5	5	-	0	0
SD	2	2	-	0	0
TN	6	4	-	2	0
TX	30	9	1	21	0
UT	5	3	-	0	2
VA	14	12	-	1	1
WA	9	8	-	0	1
WV	5	1	-	4	0
WI	10	4	-	5	1
WY	1	1	-	0	0
Totals	538 (100%)	255 (47.4%)	14	162 (30.1%)	121 (22.5%)

TABLE 2-3

UTILITIES NOT CHARACTERIZED

State	Number of Utilities Not Characterized	Total Population Served[b/] By These Utilities
AL	1[a/] (0)	0
AZ	1	110,000
CA	52[a/] (47)	4,226,000
CO	2	110,000
CT	1	60,000
DE	1	75,000
FL	7	645,000
GA	1	56,000
IL	9[a/] (0)	0
IN	2	130,000
KY	1	50,000
MD	2	228,000
MA	1	67,000
MI	10[a/] (0)	0
NJ	1	73,000
NY	5[a/] (3)	277,000
NC	2	120,000
ND	2	110,000
OH	7[a/] (5)	270,000
PA	7	522,000
RI	1	55,000
UT	2	120,000
VA	1	158,000
WA	1	50,000
WI	1	51,000
Totals	121 (92)	7,563,000

a/ Some or all of these utilities are served by a source that has already been characterized and whose population includes the population of the utility. (In addition, in California, the population served by three utilities is unknown). The number in parenthesis is the number of utilities contributing additional population (no double count) and corresponds to the population served in Column 3.

b/ The population served is estimated using data supplied by the U.S. EPA's Office of Drinking Water (except for Virginia, which is estimated using AWWA data). The data are typically 1973 values.

TABLE 2-1

POPULATION IN THE 50,000 AND ABOVE GROUP

	Population	Number of Utilities
Based on survey responses and supplementary sources	105,536,000	395
Missing utilities		
California	4,226,000	47
All others	3,337,000	45
Total	113,099,000	487

As shown in Table 2-4, data were obtained to characterize, at least partially, 395 out of 487 utilities (81.1%). These 395 utilities serve 93.3% of the identified population.

A considerable bias is present in the direct response to the survey. These data provide the best quality response and form the entire basis for cost estimates. Since a bias is present, that is, since the sample obtained is not a random one, the information obtained for the responding utilities cannot be extrapolated statistically to the nonresponding utilities. Geographically, considerable bias was introduced by the heavy response from soft-water areas produced by the telephone follow-up. The areas telephoned responded at a rate of about twice the other areas. In terms of size, a considerable bias was also present, with the smaller utilities not responding at the same rate as the larger ones. Table 2-5 shows the estimated total number of utilities by size interval, and the number of utilities responding to the survey. The response rate is also shown graphically in Figure 2-2. Note the general increase in response in the interval 50,000 to 100,000 population served. With two exceptions, the response rate stays roughly constant (between about 60 and 70%) from 100,000 to 1,000,000 population served. The largest utilities gave a lower response rate than average.

It was anticipated that the smaller utilities would not respond as well as larger ones. Figure 2-2 bears this out. The very largest utilities probably did not respond as well because of the greater complexity of their systems and the larger effort involved.

The response from utilities serving less than 50,000 was considerably less encouraging than that for the large utilities. Of the 512 utilities contacted, 54 provided responses containing some information, 7 replied but gave no useful information, and 1 refused to accept the questionnaire. Therefore, the positive response rate was 10.5% (54 utilities) and

TABLE 2-5

RESPONSE BY SIZE INTERVAL

Interval (Thousands Served)	Total Estimated Number of Utilities	Total Utilities Responding	Percent Responding
50- 60	78	22	28
60- 70	58	19	33
70- 80	38	18	47
80- 90	35	19	54
90- 100	23	14	61
100- 120	44	29	66
120- 140	23	15	65
140- 160	27	13	48
160- 180	22	13	59
180- 200	21	14	67
200- 400	54	27	50
400- 600	26	18	69
600- 800	14	9	64
800-1000	8	6	75
Above 1000	16	6	38
Totals	487	242	50

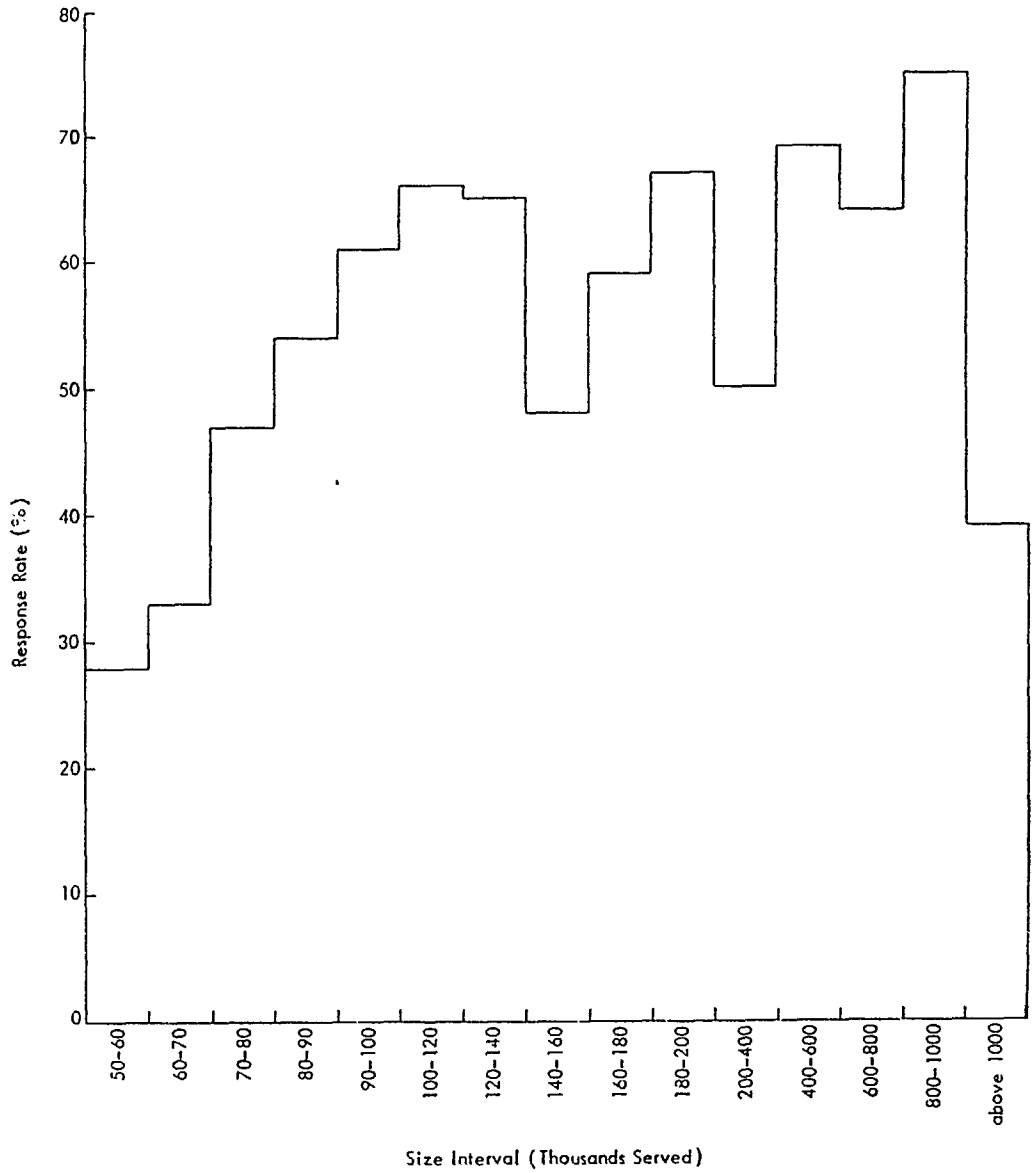

Figure 2-2 - Response Rate by Size Interval

the total response rate was 11.9% (61 utilities). Because of the very low response rate, the poor (relative to the group of larger utilities) quality of the responses obtained, and the geographical bias in the response, the results obtained for the group of smaller utilities studied were not analyzed.

2.5 Supplementary Data Sources

Supplementary data were obtained from a number of sources: state agencies, American Water Works Association data, and U.S. Geological Survey data. A bibliography of secondary sources can be found in Appendix V. Table 2-6 summarizes the states providing data.

The supplementary data consist of water quality information and some utility size information. They are useful in estimating the extent of aggressive waters in water supply systems.

TABLE 2-6

STATE SOURCES OF DATA

State Reports or Data Obtained (21)

Alabama
Arkansas
Colorado
Connecticut
Florida
Illinois
Iowa
Kansas
Kentucky
Louisiana
Massachusetts
Michigan
Minnesota
Missouri
Nebraska
New Jersey
New York
Oklahoma
South Dakota
Texas
Wisconsin

State Reports Ordered But Not Received (2)

Indiana [c/]
Tennessee

States Contacted, But Relevant Reports Not Available (12)

Arizona
California
Delaware
Georgia
Maryland
Mississippi
North Carolina
Ohio
Oregon
Pennsylvania
Virginia
Washington
West Virginia

TABLE 2-6 (CONCLUDED)

States Not Contacted (12)

Idaho [a]
Maine[a]
Montana [a]
Nevada [a]
New Hampshire[a]
New Mexico (1 utility missing)
North Dakota (2 utilities missing)
Rhode Island (1 utility missing)
South Carolina (1 utility missing)
Utah (2 utilities missing)
Vermont [b]
Wyoming [a]

---

a/ 100% response to survey.
b/ No utilities serving above 50,000 population.
c/ Received too late for use in study.

CHAPTER 3

ANALYSIS OF RESULTS

3.1 Introduction

This chapter presents the results obtained from the analysis of the information collected as described in Chapter 2. Four problems were considered:

1. The extent of occurrence of aggressive water in public water supply systems of the sizes studied;

2. The cost of internal corrosion to the utilities studied;

3. The cost of chemically stabilizing aggressive waters distributed by utilities of the sizes studied;

4. The ratio of benefits to costs associated with chemically stabilizing aggressive waters.

These problems are considered, in turn, in the following four sections.

3.2 Occurrence of Aggressive Water in Distribution Systems

The results obtained from the survey and those collected from the secondary sources were analyzed to determine the population using waters having varying degrees of aggressiveness when it entered the distribution system. The number of utilities distributing such water was also determined. Tables 3-1 and 3-2 tabulate the results. Data are presented for the survey alone, for the supplementary sources alone, and with the two combined. The data are also displayed in Figures 3-1 through 3-6.

Results have been presented for those utilities for which sufficient data were available to determine the LSI*: 388 utilities serving a combined population of 103.5 million. There are an additional 9.5 million people served by 99 utilities for which an LSI cannot be determined. These additional utilities are generally smaller than average for the size group considered. They are distributed throughout the United States; however, about half (47) are in California. The locations of the utilities which could not be characterized were given in Chapter 2. Table 3-3 describes the location of seven utilities partially characterized which were included in the survey on supplementary data groups.

* See Appendix III for a discussion concerning the calculation of LSI.

TABLE 3-1

POPULATION EXPOSED BY DEGREE OF AGGRESSIVENESS
OF WATER ENTERING DISTRIBUTION SYSTEM

	Langlier Saturation Index						
	Below -3.0	-3.0 - -2.0	-2.0 - -1.0	-1.0 - 0.0	0 - 1.0	Above 1.0	Total
Survey Results							
Population in millions	2.743	3.362	6.766	20.715	18.354	4.483	56.423
Percent in Interval	4.86	5.96	11.99	36.71	32.53	7.95	100.0
Supplementary Sources							
Population in millions	1.609	3.466	14.144	20.041	7.252	0.514	47.026
Percent in Interval	3.42	7.37	30.08	42.62	15.42	1.09	100.0
Total-All Sources							
Population in millions	4.352	6.828	20.911	40.756	25.606	4.997	103.449
Percent in Interval	4.20	6.60	20.21	39.40	24.75	4.83	100.0

TABLE 5-2

NUMBER OF UTILITIES BY DEGREE OF AGRESSIVENESS OF WATER DISTRIBUTED

	Langlier Saturation Index						
	Below -3.0	-3.0 - -2.0	-2.0 - -1.0	-1.0 - 0.0	0.0 - 1.0	Above 1.0	Total
Survey Results							
Number of utilities	17	21	31	86	65	19	239
Percent in interval	7.11	8.79	12.97	36.00	27.20	7.95	100.0
Supplementary Sources							
Number of utilities	9	15	19	64	39	3	149
Percent in interval	6.04	10.07	12.75	42.95	26.17	2.01	100.0
Totals-All Sources							
Number of utilities	26	36	50	150	104	22	388
Percent in interval	6.70	9.28	12.89	38.66	26.80	5.67	100.0

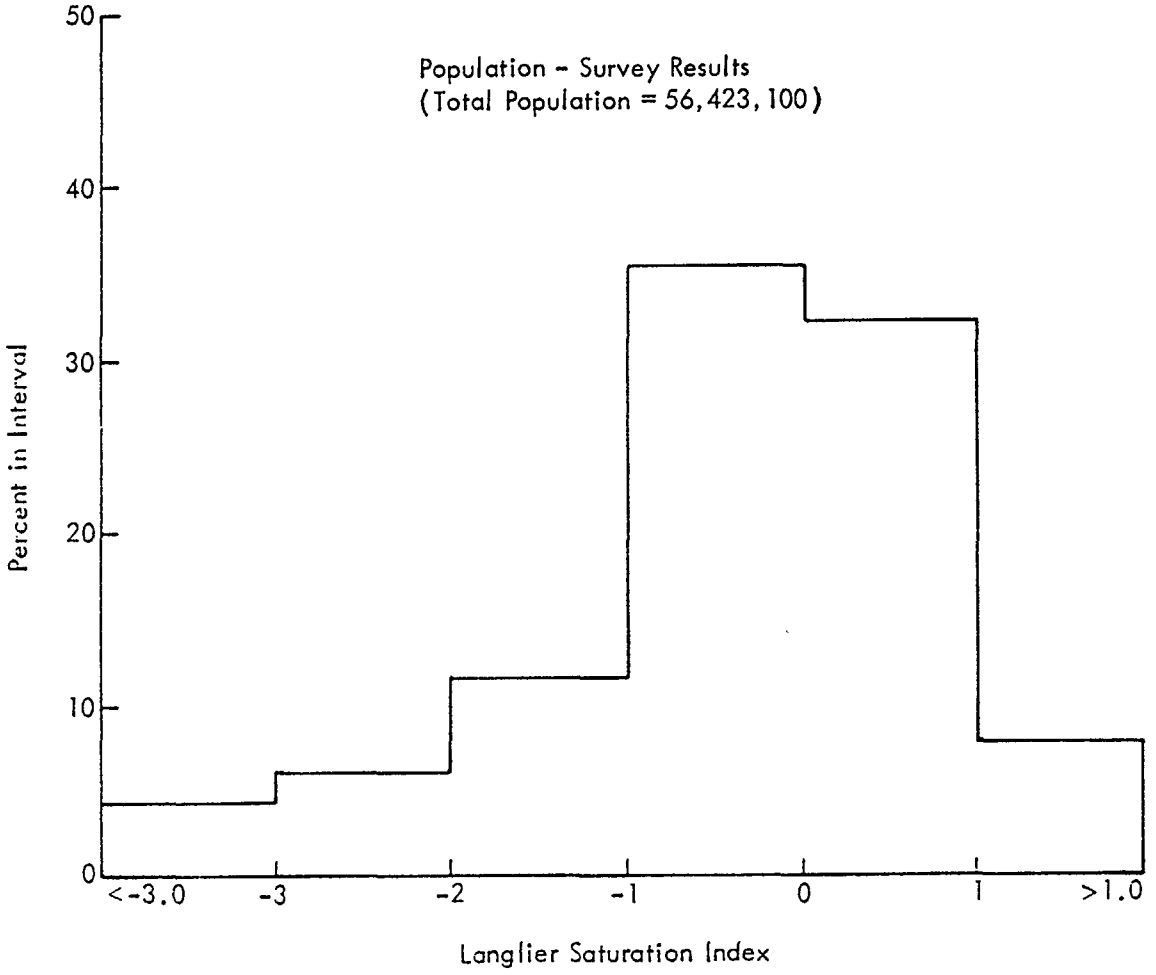

Figure 3-1 - Portion of Population by Degree of Aggressiveness of Water Entering Distribution System (Survey Result)

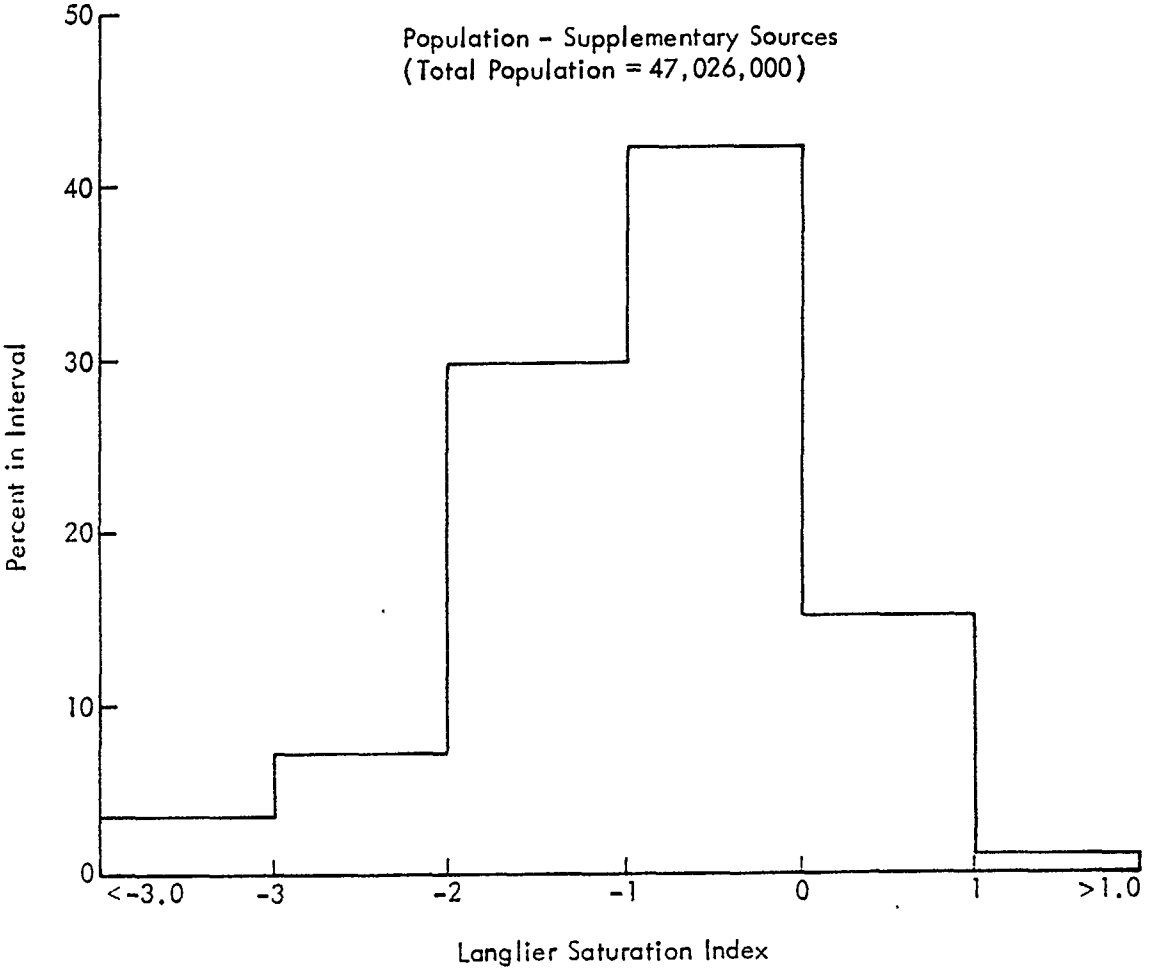

Figure 3-2 - Portion of Population by Degree of Aggressiveness of Water Entering Distribution System (Supplementary Sources)

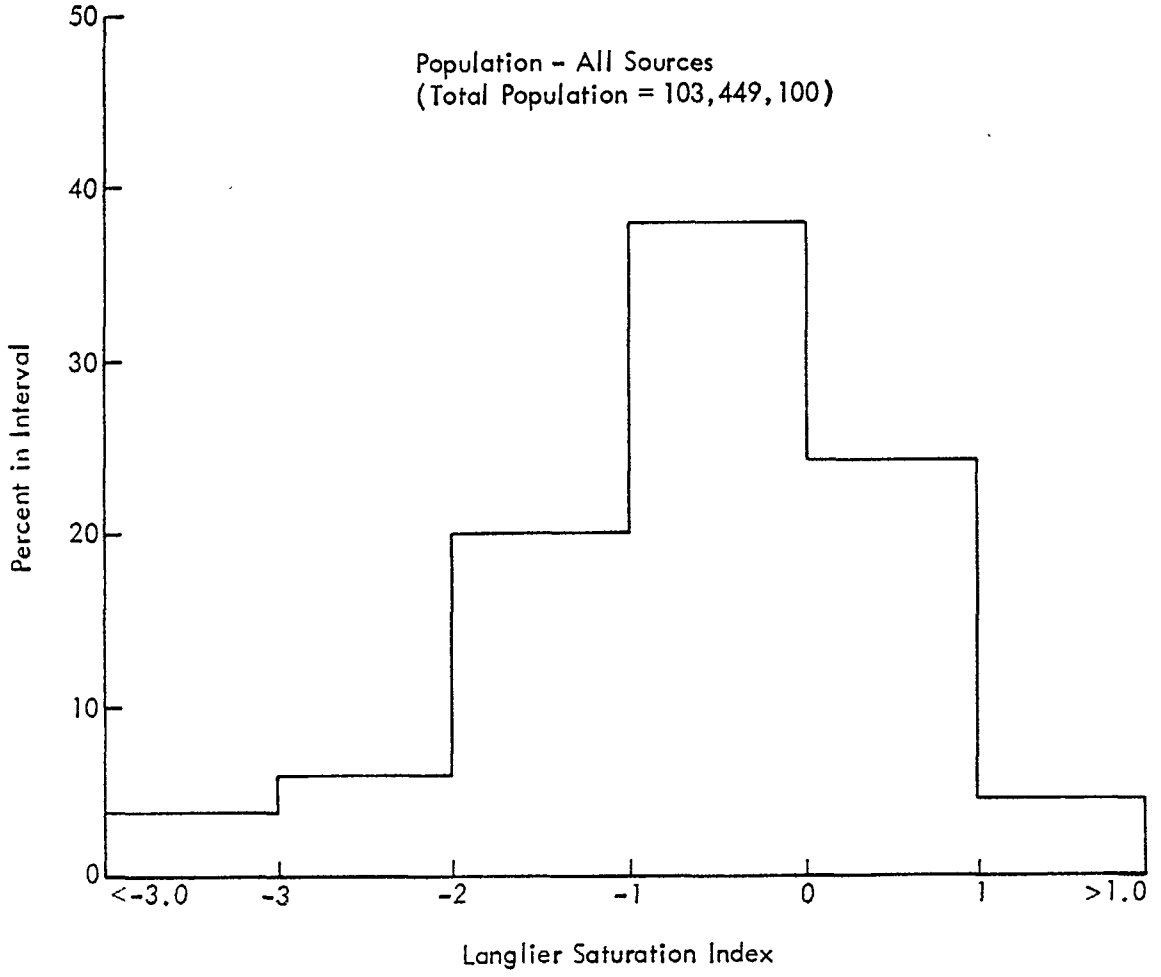

Figure 3-3 - Portion of Population by Degree of Aggressiveness of Water Entering Distribution System (All Sources Combined)

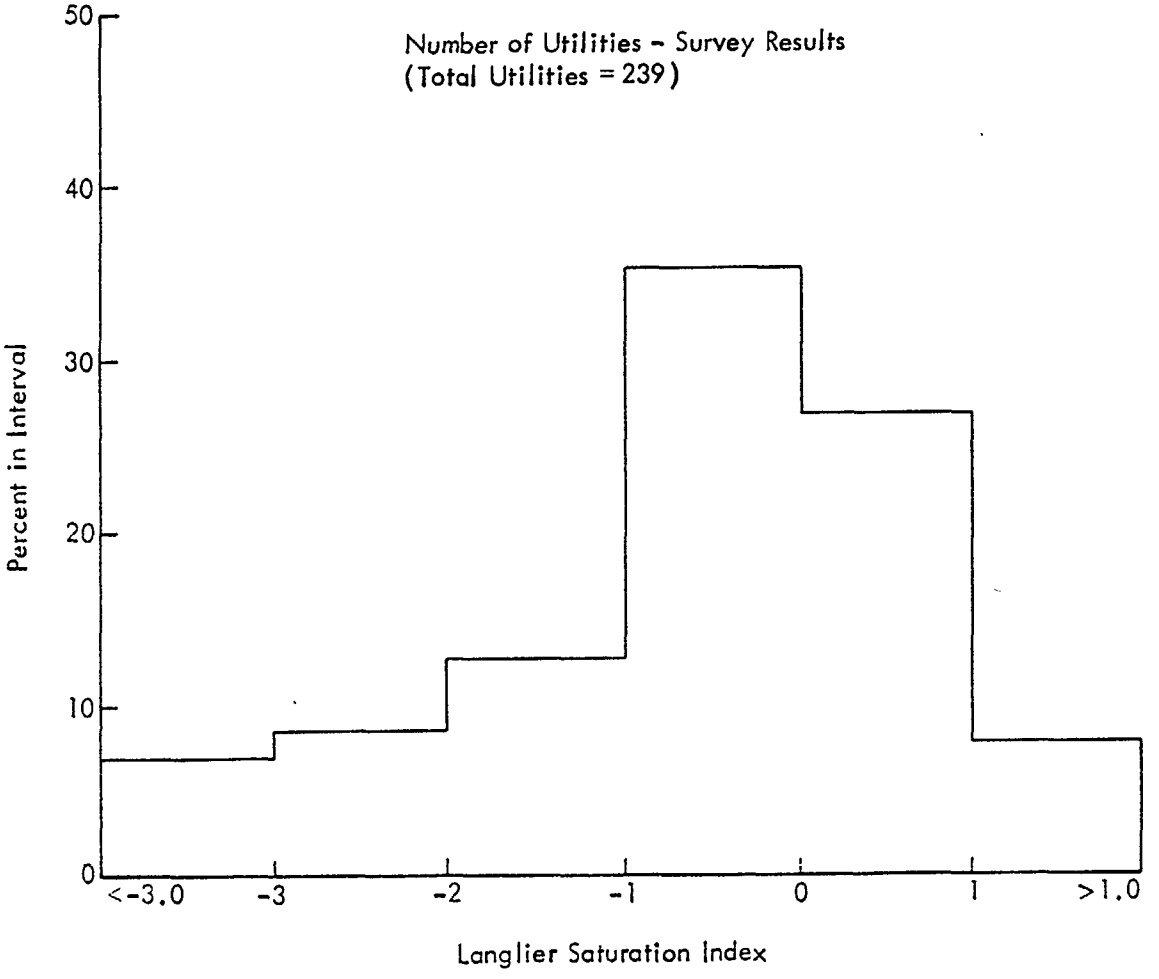

Figure 3-4 - Portion of Utilities by Degree of Aggressiveness of Water Distributed (Survey Results)

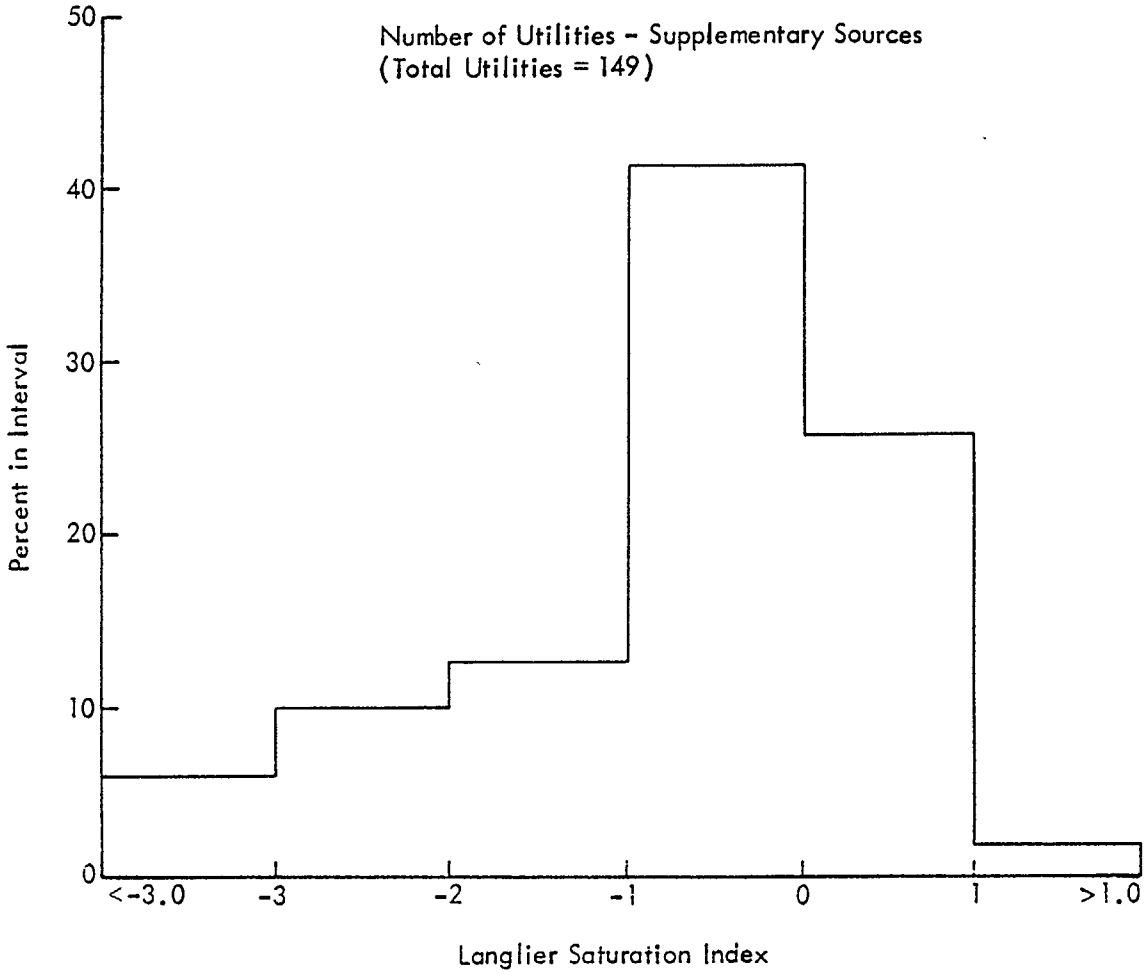

Figure 3-5 - Portion of Utilities by Degree of Aggressiveness of Water Distributed (Supplementary Sources)

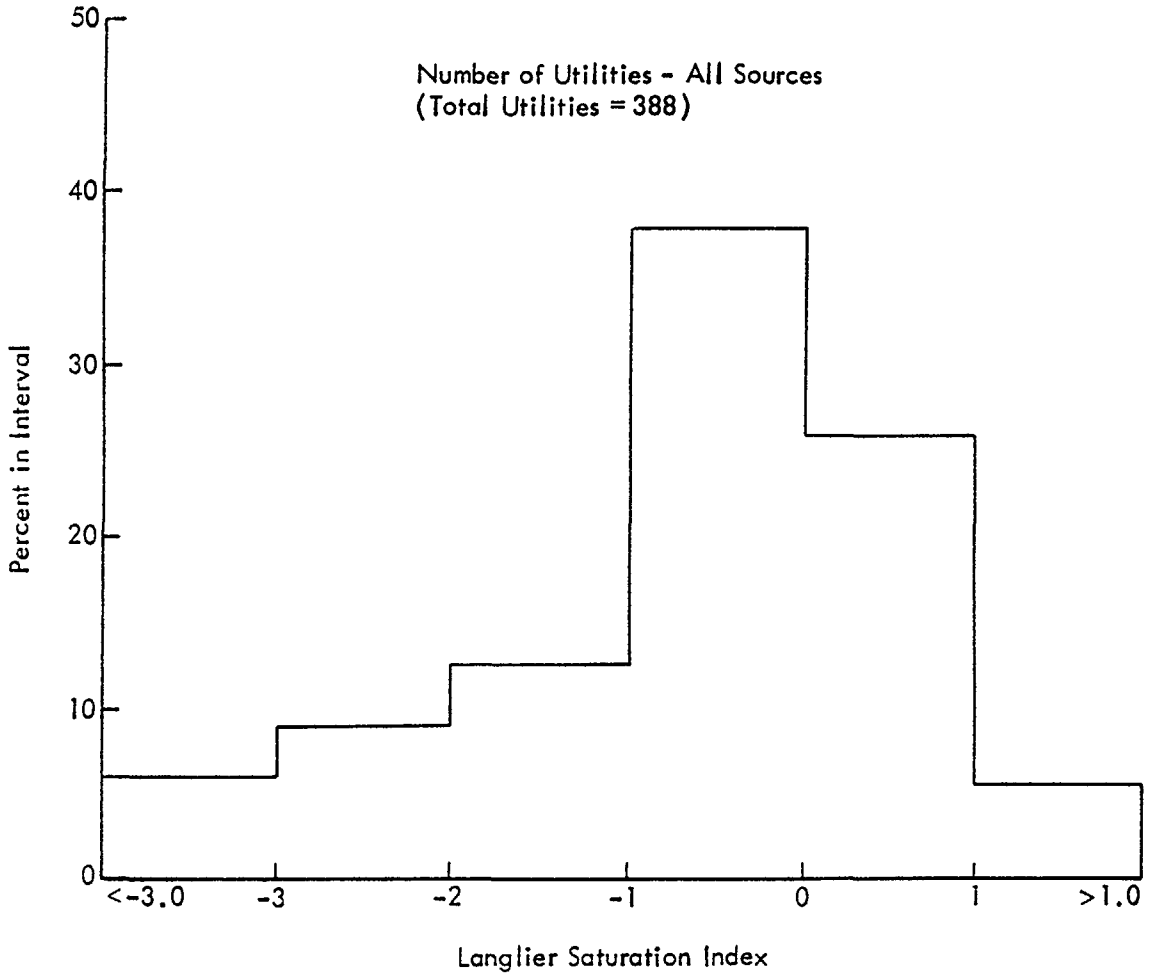

Figure 3-6 - Portion of Utilities by Degree of Aggressiveness of Water Distributed (All Sources Combined)

The utilities in Table 3-3 and those in Table 2-3 can be grouped roughly by expected values of LSI. Table 3-4 shows how these additional data can be combined with the results of Tables 3-1 and 3-2 to place upper limits on the population and utilities associated with rather aggressive waters. In making the calculations in Table 3-4, utilities were assumed to have as low a value of LSI as seemed possible, based on general results for the state in which the utility is located.

In obtaining the results in Table 3-4 the following was assumed:

(1) All the utilities not characterized (see Table 2-3) in the following states distribute water with an LSI less than -2.0: Connecticut, Delaware, Florida, Georgia, Kentucky, Maryland, Maine, New Jersey, North Carolina, Pennsylvania, Rhode Island, Virginia, and Washington.

(2) All utilities not characterized in New York distribute water with an LSI less than -1.0, but greater than -2.0.

(3) All utilities not characterized in the following states distribute water with an LSI greater than -1.0: Arizona, California, Colorado, Indiana, North Dakota, Ohio, Utah, and Wisconsin.

(4) For the utilities with partial data given in Table 3-3, all except the utility in California (LSI$\approx$0) were assumed to distribute water with an LSI less than -1.0, but greater than -2.0.

With the possible exception of assumption (3) concerning California utilities, these seem to be very conservative assumptions.

It was assumed that the California utilities involved had rather stable water (LSI $>$ -1.0). Forty-seven utilities in California could not be characterized in terms of water quality. These utilities represent about one-half of all those in the U.S. which could not be characterized. Therefore, the assumptions concerning these California utilities are the most important of those made for any state.

Those utilities characterized in California serve about 9.6 million people and include virtually all of the large utilities in the state. Of these, only two utilities, serving a combined population of about 130,000, distribute water with an LSI less than or equal to -1.0 (the actual values are -1.0 and -1.1).

Those California utilities not characterized serve about 4.2 million people. Of these, 2.3 million are served by a combination of water supplied by the Metropolitan Water District of Southern California (MWDSC) and by wells. The water which MWDSC provides is stable and it seems fair to assume that the well water in Southern California is also.

TABLE 3-3

UTILITY LOCATIONS - PARTIAL DATA

State	Population	Number of Utilities	Approximate LSI
CA	200,000	1	LSI $\approx$ 0
FL	380,000	2	-1 < LSI < 0
NJ	130,000	2	LSI $\approx$ -1.0
NY	169,000	1	?
TX	1,150,000	1	LSI $\approx$ -1.0
Total	2,029,000	7	

TABLE 3-4

ESTABLISHING AN UPPER LIMIT ON POPULATION EXPOSED TO WATER HAVING AGGRESSIVE CHARACTERISTICS WHEN IT ENTERS THE DISTRIBUTION SYSTEM

Source	Population in millions	Number of utilities
For LSI < -2.0		
Survey + supplementary sources--complete quality data	11.280	62
Survey + supplementary sources--inadequate quality data	0 (est)	0 (est)
Not characterized	2.159 (est)	27 (est)
Total	13.439	87
For LSI < -1.0		
Survey + supplementary sources--complete quality data	32.191	112
Survey + supplementary sources--inadequate quality data	1.829 (est)	6 (est)
Not characterized	2.436 (est)	30 (est)
Total	36.456	148

An additional 1.1 million people are served by other uncharacterized utilities in Southern California. Again, it seems reasonable to assume that these utilities supply water with an LSI above -1.0.

There are about 0.8 million people in Northern and Central California served by utilities whose water cannot be characterized. The major utilities in Northern California which could be characterized have LSI's above -1.0. Since only two small California utilities were identified which have an LSI of -1.0 or less, it seems fair to assume that no significant factor of the 0.8 million is served by utilities whose water has an LSI below -1.0.

If some of the California utilities which could not be characterized distribute aggressive water, then the totals in Table 3-4 will increase, as will the percentages given in Table 3-5. Note that to obtain a 1% increase in the "population exposed" bounds in Table 3-5 requires a population of 1.13 million. Therefore, if one-half of the 0.8 million population discussed in the preceding paragraph is served by utilities distributing aggressive water (LSI < -1.0), the "percent population exposed" values in Table 3-5 will increase by about 0.3%. The results obtained, therefore, seem insensitive to any likely erroneous assumptions concerning California utilities.

TABLE 3-5

ESTIMATED OCCURRENCE OF AGGRESSIVE WATERS

	Percent Population Exposed[a/]	Percent Utilities Distributing
LSI < -2.0		
Lower bound	10.0	12.7
Upper bound	11.9	18.3
LSI < -1.0		
Lower bound	28.5	23.0
Upper bound	32.2	30.4

a/ Based on the character of the water when it enters the distribution system.

Based on a total population served of 113.1 million and 487 utilities, the fraction of the population and the number of utilities associated with an LSI less than -2.0* and an LSI less than -1.0 can be estimated. The results from the survey and the supplementary sources place a reasonable lower bound on the numbers in each group. These results, plus conservative judgments (i.e., assume as low an LSI as seems reasonable) about the waters which were not characterized, allow an upper bound to be estimated. Table 3-4 shows estimate of the upper and lower bounds on populations and numbers of utilities. Table 3-5 shows percentage total population and percentage of utilities in the two categories.

Note that even rather conservative assumptions about the missing utilities do not result in upper limits on the population that are greatly different from the lower limits. However, because the utilities involved in the uncertain group are relatively small, the portion of the utilities distributing water with an LSI less than -1.0 or -2.0 is more uncertain, that is, there is a wider spread between the upper and lower bounds.

Since the above calculations are based on measured values and on conservative assumptions about the utilities that were not characterized, the numbers in Table 3-5 are very firm estimates of upper and lower limits on the populations and utilities involved. Since no sampling was involved, there is no problem of sampling error. The major possible sources of error, in order of importance, are: omission of utilities which were not identified, use of outdated or inappropriate data from supplementary sources, inaccurate data supplied by utilities in the survey, and double counting of population. Since there is no reason to believe that these sources of error would introduce any significant bias into the calculations, the results shown in Table 3-5 are considered to be accurate. A bias would be present if 10 million people who lived in New England were not identified. Such an omission would mean that the results in Table 3-5 are gross underestimates. However, any unidentified population is, in all likelihood, widely distributed throughout the United States. There is no reason to expect that appropriate utilities were less likely to be identified in one part of the country than in another.

Therefore, the portion of the U.S. population (served by utilities with 50,000 or more population) exposed to water with an LSI less than -2.0 (when it enters the distribution system) is in the range of 10.0-11.9%. That exposed to an LSI of -1.0 or less is in the range of 28.5-32.3%. As Table 3-4 shows, these portions represent quite significant numbers of people: 11.3-13.4 million in the first instance and 32.3-36.5 million in the second.

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* The phrase "less than -2.0" signifies that -3.0 is less than -2.0, etc.

Aggressiveness and Ryznar indices were also determined for all utilities studied. These did not provide any useful information beyond that reported using LSI, and the results have not been included. In particular, the results obtained using AI can be found from those reported for LSI (with very small error) by simply adding 12 to the LSI values given.

It is interesting to compare the distribution of utilities by aggressiveness of water distributed found here with the results of Millette et al. (1979). The following tabulation provides a comparison.

	Portion of Utilities	
Character of Water Distributed	Millete et al. 1969	Present Study
Highly aggressive water (AI less than 10.0; LSI less than -2.0)	16.5%	16.0%
Moderately aggressive water ($10 < AI < 12$; $-2.0 < LSI < 0.0$)	52.0%	51.5%
Nonaggressive water (AI greater than 12.0; LSI greater than 0.0)	31.5%	32.5%

The results for the "present study" column were taken from Table 3-2 using data from "all sources." The two sets of results are essentially identical; the differences are less than the uncertainties in the results obtained here that can be inferred from Table 3-5.

3.3 Costs of Internal Corrosion to Utilities

The survey questionnaire contained a number of questions designed to shed light on the question: "What does internal corrosion cost water utilities?" The relevant questions on the survey were: first, the question related to overall costs of water-related corrosion; second, the questions concerning pipe replacement; and third, the questions concerning the utility's budget. The information obtained from these questions will be considered in turn. Figure 3-7 shows the location of utilities reporting losses due to internal corrosion.

3.3.1 Reported costs of water-related corrosion: The question "What are your annual costs due to water-related corrosion?" was asked. Table 3-6 lists all utilities which indicated that they were experiencing

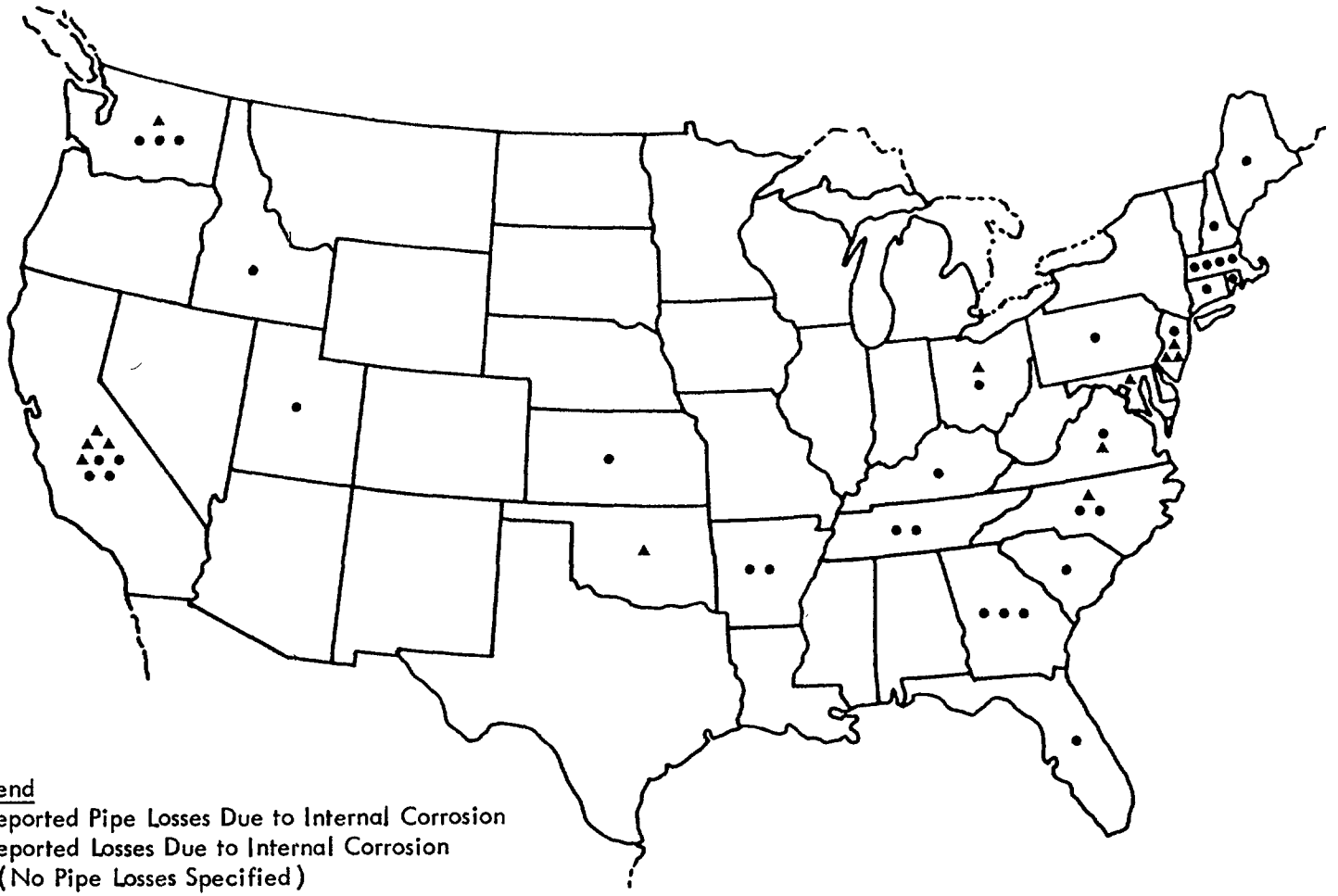

Figure 3-7 - Losses Due to Internal Corrosion

TABLE 3-6

LOSSES DUE TO INTERNAL CORROSION
(dollars/year)

(1) Utility Code Number	(2) LSI	(3) Reported Cost of Water-related Corrosion	(4) Total Estimated Cost of Pipe Replacements	(5) Estimated Costs of Steel Pipe Replacements	(6) Estimated Costs of Galvanized Pipe Replacements	(7) Estimated Costs of Unlined Cast Iron Pipe Replacements [a] (4)-(5)-(6)
1	-1.2	31,700	37,000	-	37,000	0
2	-0.8	500,000	351,400	-	351,400	0
3	-1.1	17,900	-	-	-	-
4	+1.4	10,800	-	-	-	-
5	0.0	-	277,200	-	-	277,000
6	-0.2	20,000	14,800	14,800	-	0
7	-1.0	-	29,600	11,100	18,500	0
8	-2.4	6,600	5,500	-	-	5,500
9	+0.3	210,000	91,000	35,000	-	56,000
10	-0.4	1,600	2,800	-	2,800	0
11	-0.7	15,000	5,300	-	5,300	0
12	-1.0	-	88,700	-	73,900	14,800
13	-0.9	-	443,500	388,100	55,400	0
14	0.0	-	38,400	-	-	38,400
15	-3.7	45,100	101,600	-	101,600	0
16	-1.2	13,200	-	-	-	-
17	-3.8	-	72,800	-	-	72,800
18	-2.5	-	8,400	-	-	8,400
19	-3.3	5,280,000	1,108,800	-	-	1,108,800
20	-1.7	-	499,000	-	-	499,000
21	-3.6	50,000	56,500	-	-	56,500
22	-0.9	175,000	42,000	-	-	42,000
23	-2.5	400,000	-	-	-	-
24	-0.8	75,000	-	-	-	-
25	-3.6	-	295,700	295,700	-	0
26	+0.1	110,000	96,200	74,000	-	22,200
27	-1.9	18,000	-	-	-	-
28	-0.5	-	110,900	-	-	110,900
29	+0.4	-	3,500	2,800	-	700
30	-1.5	10,000	221,800	-	-	221,800
31	-2.9	-	60,000	37,000	900	22,100
32	-0.9	120,000	35,000	-	35,000	0
33	+0.1	-	739,200	-	-	739,200
34	0.0	-	277,200	221,800	-	55,400
35	-0.6	54,500	-	-	-	-
36	-2.8	10,000	110,900	110,900	-	0
37	-3.0	-	184,800	184,800	-	0
38	-4.1	-	136,800	99,800	37,000	0
39	+1.0	40,000	-	-	-	-
40	-0.7	-	110,900	110,900	-	0
41	+0.1	45,000	-	-	-	-
42	-0.5	30,000	-	-	-	-
43	-0.3	-	665,300	-	-	665,300
44	+0.2	300,000	-	-	-	-
45	-2.8	445,000	-	-	-	-
46	-1.7	-	887,000	-	-	887,000
47	-0.1	265,000	-	-	-	-
For 47 Utilities Avg = -1.2		8,299,000	7,209,500	1,586,700	718,800	4,904,000

a/ These costs are primarily for cast iron replacements, but this column includes miscellaneous items as well and includes storage losses.

losses due to internal corrosion. Column (3) of that table gives the annual corrosion costs provided by the utilities. A total of 28 utilities in the 50,000 or above group reported costs. Numerous others indicated that they did not know what their losses might be. As Table 3-6 shows, the total costs reported were $8.299 million annually. These utilities served a total of 7,245,000 people. Therefore, the average cost per capita is $1.15 per year averaged over all the utilities. There is, of course, a considerable variation. In particular, one utility contributes $5.28 million of the total. Without this utility, the total is $3.019 million per year and the average cost per capita is $0.42 per year.

Annual costs due to water-related corrosion consist of costs associated with losses of transmission and distribution pipes, meters, storage facilities, residential and industrial plumbing and piping, and home appliances (e.g. heat exchange equipment). Quantification of costs attendant to corrosion of all these items was beyond the scope and resources of the study. Transmission and distribution piping losses tend to dominate the losses when they occur in water utilities. Only pipe replacement costs and cost of losses of storage facilities were considered in the economic impact analysis. When a utility reporting losses also supplied pipe replacement information, the calculated cost of pipe replacements frequently was in good agreement with reported costs, lending credibility to both numbers.

The quality of the "water-related corrosion costs" provided was variable, with some utilities supplying actual cost information from their records, and others making order of magnitude estimates. However, because of general consistency found between these reported costs and estimated costs of pipe replacements, the cost data were accepted as being of useful accuracy.

3.3.2 Costs estimated from pipe replacement: Using the data provided by utilities on amount, type, and size of pipe replaced annually, it is possible to estimate the cost of pipe replacements due to internal corrosion. Pipe replacement costs can vary widely depending upon location. Older cities often have layers of concrete, asphalt, and brick, buried trolley tracks, and other buried utility service lines with which to contend, so they can experience considerable expense in pipe replacement. In 1967, Philadelphia used $35/ft as an average cost for re-lays of 6-8 in. diameter metallic pipe (Radziul et al., 1967). At present labor and material prices, this number would be increased substantially.

The pipe replacements reported were generally of smaller or distribution sized pipe (6-8 in. diameter was very common); the cities replacing pipe vary widely in size and location. Results of consultations with an engineering firm experienced in the area of pipe replacement

suggest that $3.50 per diameter-in.-ft is a reasonable re-lay cost, assuming an even mix of residential and commercial replacements. This cost is certainly less than the number given above for Philadelphia, but appears to agree well with costs provided by many of the utilities studied.

Using the $3.50 value, the estimated costs shown in Columns 4 through 7 of Table 3-6 were obtained. These columns give estimated total costs of pipe replacement, and estimated costs for replacement of cast iron, steel and galvanized pipe. Table 3-6 shows total costs of $4,904,000/year for cast iron (see footnote to Table 3-6) and a total of $7,209,500/year for all pipe replacements reported. These utilities served a combined population of 6,550,450. The annual costs per capita are $0.75 for cast iron pipe replacements and $1.10 for total pipe replacements. Again, a few utilities contributed a disproportionate share of losses. Removing one utility which serves 55,000 people and which has cast iron losses of $1,108,800 per annum, gives $0.58/year and $0.93/year per capita costs for cast iron and total replacements, respectively.

The results for pipe replacements are in rough agreement with those found in the preceding section.

3.3.3 Inferences from other cost data: Cost data were obtained for a variety of categories, as the survey form shows. The three major groups were (1) costs for water treatment, (2) cost for water distribution, and (3) costs for water-related corrosion losses and prevention. In the first two categories, costs were obtained for operation, maintenance, capital replacement, and depreciation.

These cost data were analyzed by grouping the utilities in terms of size and by aggressiveness of water. For each cost category, costs for each utility group were found on an annual-per-capita-served basis, on a per-unit-volume-of-water-distributed basis, and on a per-unit-length-of-distribution-system basis.

The analysis yielded no well-defined relationship between any specific cost and degree of aggressiveness of the water. The analysis was complicated by the fact that utilities do not report costs uniformly. Also, many utilities reported no cost information or only portions of the information requested.

The mean per capita costs of water treatment and distribution are in the neighborhood of $10-20 per capita per year. If $0.50-1.00 were a typical annual per capita cost of internal corrosion, such a cost would be 5-10% of the total and would be difficult to separate from the background, particularly given the quality of the cost data available.

3.3.4 Best estimates of internal corrosion losses: Certain utilities which estimate corrosion losses do not report pipe replacements and vice versa. Some portions of the total reported losses include costs other than pipe replacements. For some of the utilities whose only losses are due to pipe replacements, the reported costs and the estimated costs based on pipe replacements are in reasonably good agreement--compare utilities 1, 6, 8, 10, or 21, in Table 3-6.

Taking the most reasonable of the reported cost values or the estimated pipe replacement costs gives the results in Table 3-7. If the two costs were similar, the reported costs were used. If the estimated pipe replacement costs were much larger, the estimated costs were used. If only one of the two costs was available, that value was used. If the reported costs was much larger than the estimated cost, the former was used, when there was no reason to do otherwise. For example, for utility 19 in Table 3-6 the reported cost is $5.28 million based on a $100/ft replacement cost. That value seems very high and the estimated pipe replacement costs seem more reasonable.

Selecting what seemed to be the best estimate of water-related corrosion losses for each utility gave the results in Table 3-7. The total annual loss for the 47 utilities is estimated at $9,369,800 with $6,979,000 due to replacements not related to steel or galvanized pipe.

These utilities serve a total of 10,337,560 people, giving annual per capita costs of $0.91 for total internal corrosion costs and $0.68 for costs not related to steel or galvanized pipe. Removing the utility with highest cost reduces the population to 10,282,560 and the costs to $8,261,000 total and $5,870,200 for cast iron pipe replacements (see footnote to Table 3-7). This gives annual per capita costs of $0.80 and $0.57, respectively.

3.3.5 Summary: Table 3-8 summarizes the results for losses due to internal corrosion. The various approaches discussed above are summarized in terms of annual per capita costs. Assuming that the utilities can properly evaluate their losses, the table suggests average total losses equivalent to about $0.80-$1.00 per capita per year and average costs for other than steel or galvanized replacements (primarily cast-iron pipe) of about $0.60-$0.70 per capita per year. These costs, of course, only apply to the group of utilities experiencing internal corrosion problems. Due to the bias in the survey response, these results cannot be extrapolated in a statistically meaningful way to the group of utilities who did not respond to the survey.

TABLE 3-7

BEST ESTIMATE OF LOSSES DUE TO INTERNAL CORROSION

(1) Utility Code Number	(2) LSI ≤ -0.5	(3) Estimated Losses (dollars/year)	(4) Costs of Steel/Galvanized Pipe Replacements (dollars/year)	(5) Costs of Unlined Cast Iron Pipe Replacements[a] (dollars/year) (3)-(4)
1	Yes	31,700	-	31,700
2	Yes	500,000	425,000	75,000
3	Yes	17,900	-	17,900
4	No	10,800	-	10,800
5	No	277,200	-	277,200
6	No	20,000	12,000	8,000
7	Yes	29,600	29,600	0
8	Yes	6,600	-	6,600
9	No	210,000	38,500	171,500
10	No	1,600	1,600	0
11	Yes	15,000	15,000	0
12	Yes	88,700	73,900	14,800
13	Yes	443,500	443,500	0
14	No	38,400	-	38,400
15	Yes	45,100	45,100	0
16	Yes	13,200	-	13,200
17	Yes	72,800	-	72,800
18	Yes	8,400	-	8,400
19	Yes	1,108,800	-	1,108,800
20	Yes	499,000	-	499,000
21	Yes	50,000	-	50,000
22	Yes	175,000	-	175,000
23	Yes	400,000	-	400,000
24	Yes	75,000	-	75,000
25	Yes	295,700	295,700	0
26	No	110,000	85,000	25,000
27	Yes	18,000	-	18,000
28	Yes	110,900	-	110,900
29	No	3,500	2,800	700
30	Yes	221,800	-	221,800
31	Yes	60,000	37,900	22,100
32	Yes	120,000	120,000	0
33	No	739,200	-	739,200
34	No	277,200	221,800	55,400
35	Yes	54,500	-	54,500
36	Yes	110,900	110,900	0

TABLE 3-7 (CONCLUDED)

(1) Utility Code Number	(2) LSI ≤ -0.5	(3) Estimated Losses (dollars/year)	(4) Costs of Steel/Galvanized Pipe Replacements (dollars/year)	(5) Costs of Unlined Cast Iron Pipe Replacements[a] (dollars/year) (3)-(4)
37	Yes	184,800	184,800	0
38	Yes	136,800	136,800	0
39	No	40,000	-	40,000
40	Yes	110,900	110,900	0
41	No	45,000	-	45,000
42	No	30,000	-	30,000
43	No	665,300	-	665,300
44	No	300,000	-	300,000
45	Yes	445,000	-	445,000
46	Yes	887,000	-	887,000
47	No	265,000	-	265,000
Totals		9,369,800	2,391,800	6,979,000

a/ These costs are primarily for cast iron replacements, but this column includes miscellaneous and storage losses.

TABLE 3-8

COSTS OF INTERNAL CORROSION,
UTILITIES REPORTING LOSSES

Basis for Calculation	Total Annual Costs per Capita	Total Costs Other Than for Steel/Galvanized Pipe Replacements	No. of Utilities	Total Population
Reported costs	$1.15	Unknown	28	7,244,580
Reported costs without highest cost utility	$0.42	Unknown	27	7,189,580
Estimated from pipe replacements	$1.10	$0.75	35	6,550,450
Estimated from pipe replacements without highest cost utility	$0.93	$0.58	34	6,499,450
"Best estimate" (See Table 3-7)	$0.91	$0.68	47	10,337,560
"Best estimate" without highest cost utility	$0.80	$0.52	46	10,282,560

3.4 Costs of Treatment to Prevent Corrosion

Aggressive waters can be chemically stabilized to reduce internal corrosion losses. Chemical treatment alone cannot eliminate corrosion problems, but should result in decreased corrosion.

For those utilities reporting internal corrosion problems and which have an LSI below -0.5, the costs of adding chemicals to stabilize the water were estimated. Similar estimates were also made for all other utilities for which LSI is less than -0.5, but which reported no losses.

For discussion purposes, two chemical stabilization approaches were considered. The first approach involved the addition of lime until an LSI of 0.0 was reached. If an LSI of 0.0 was not reached by the time the pH had risen to 9.5, carbon dioxide was added along with the lime to maintain a pH of 9.5. (Substitutes for carbon dioxide exist, e.g., soda ash or sodium bicarbonate.) The second approach required minimum values of alkalinity and calcium concentration and avoided undesirable pH values. A minimum alkalinity of 40 mg/liter as $CaCO_3$, and a minimum calcium concentration of 40 mg/liter as $CaCO_3$ were required. A final pH of 7.3 or below, or a pH of 8.6, was also required. A water having these characteristics is desirable from the point of view of stability. Lime and CO_2 were used to provide the needed chemical additions. Chemicals were added until an LSI of 0.0 was obtained along with the above characteristics.

The details involved in determining chemical additions are presented in Appendix I. The two approaches to chemical stabilization which have just been discussed will be called Treatments I and II. Treatment II refers to the more extensive stabilization. Appendix II discusses the basis for estimating costs of chemical additions.

Table 3-9 lists estimated costs for stabilizing waters for those utilities with LSI's below -0.5 and which experience losses due to internal corrosion.

Of the 47 utilities reporting losses, 31 have an LSI below -0.5. Costs of stabilization can be found for those utilities. As Table 3-9 shows, the total annual costs are $1.29 million for Treatment I and $3.624 million for Treatment II. Those utilities serve 5.572 million people, so the annual per capita costs are $0.20 and $0.65 for Treatments I and II, respectively. For individual utilities, the annual per capita costs range from $0.06 (for Utility 45) to $0.69 (for Utility 17) for Treatment I and range from $0.08 to $4.69 for Treatment II.

In addition to those utilities reporting losses on the survey, there are many others with LSI's less than -0.5 which report no losses. There were an additional 86 utilities with population served above 50,000

TABLE 3-9

COSTS OF STABILIZATION FOR UTILITIES
WITH INTERNAL CORROSION LOSSES

Utility Code Number	Initial LSI	Population Served (thousands)	Volume of Water (mgd)	Annual Costs of Treatment (thousands of dollars) I	II
1	-1.2	100.0	11.5	39.6	104.1
2	-0.8	75.0	19.4	21.9	113.3
3	-1.1	62.2	9.5	21.4	64.6
7	-1.0	65.0	12.0	29.1	30.8
8	-2.4	82.0	15.6	26.0	107.1
11	-0.7	100.0	12.0	21.7	76.1
12	-1.0	460.0	56.5	81.4	299.0
13	-0.9	110.0	22.0	28.3	28.9
15	-3.7	146.5	22.1	62.6	144.9
16	-1.2	70.0	9.7	24.4	24.8
17	-3.8	65.6	10.7	45.4	111.3
18	-2.5	75.0	8.8	22.6	80.7
19	-3.3	55.0	6.1	29.4	66.3
20	-1.7	128.0	13.1	37.1	99.3
21	-3.6	110.0	14.0	61.7	122.7
22	-0.9	54.0	6.5	Data inadequate	
23	-2.5	420.0	65.0	51.3	306.4
24	-0.8	113.0	16.6	Data inadequate	
25	-3.6	130.0	25.0	75.7	189.7
27	-1.9	160.0	11.7	22.7	62.3
28	-0.5	305.5	50.7	25.5	25.5
30	-1.5	54.0	7.5	21.9	42.4
31	-2.9	79.9	13.6	39.3	122.1
32	-0.9	400.0	65.0	29.3	36.3
35	-0.6	166.6	19.2	22.5	22.7
36	-2.8	90.0	10.5	24.4	83.9
37	-3.0	110.0	10.9	35.4	87.6
38	-4.1	200.0	90.0	100.5	537.1
40	-0.7	100.0	17.6	24.9	25.2
45	-2.8	992.1	117.9	58.6	470.0
46	-1.7	660.0	72.0	44.4	139.1
Totals		5,572.3		1,129.2	3,624.0

and an LSI less than -0.5 who responded. The cost of Treatment II for these utilities is $9,356,000 annually. These utilities serve 23,275,000 people for an average per capita annual cost of $0.41. The annual per capita cost varies from $0.04 to $2.05 for Treatment II. For Treatment I the total annual cost is $3,293,000 giving an annual per capita cost of $0.14 and a range of annual per capita costs of $0.03 to 0.67.

There were also 60 utilities characterized using data from supplementary sources, which have a population served above 50,000, and an LSI below -0.5. Of course, no reports concerning corrosion losses are available for this group. Also, the water quality data were generally less current than those supplied by the utilities themselves. These 60 utilities serve 23,761,400 people. The total annual cost of stabilization would be $3,032,000 for Treatment I and $9,007,000 for Treatment II. The per capita annual costs are therefore $0.13 and $0.38 for Treatments I and II, respectively.

Tables 3-10 and 3-11 summarize and amplify the cost estimate information related to chemical stabilization. Table 3-10 breaks the costs down into the various components: chemical costs, capital costs, and labor costs. The difference between the sum of these three costs and the total costs is the cost of maintenance. Table 3-12 shows the cost components as percentages of the total. As would be expected, the relative importance of chemical costs increases considerably for Treatment II.

Table 3-13 provides a summary of estimated stabilization costs. These costs are for all those utilities identified which have an LSI less than -0.5. The capital expenditures are the costs required for the CO_2 and lime systems as discussed in Appendix I. These capital expenditures were assumed to be financed by Municipal Water Revenue Bonds at 6% interest for 20 years. This assumption yields the annual capital cost in the table. Operation and maintenance costs (O&M) are the sum of chemical cost, labor costs, and maintenance costs from Table 3-10. Annual maintenance is assumed to be 1% of the capital expenditure cost.

The approach that has been used in arriving at the estimate of national economic impact given in Table 3-13 is very similar to that outlined in the Federal Register (1978) for determining the economic impact associated with removal of trihalomethanes and synthetic organic chemicals from drinking water. In essence, the impacted utilities were identified and the costs involved in treatment for each impacted utility were determined. These costs were combined to give the results shown in Table 3-13.

The added impact associated with the 92 utilities whose water quality could not be characterized (cf. Table 2-3) can also be estimated. A perusal of Table 2-3 suggests that probably no more than about 50% of the 92 utilities have waters with an LSI below -0.5 (this is near the national average). These "missing" utilities are smaller than average and therefore the capital costs for them will be higher than average.

TABLE 3-10

ESTIMATED ANNUAL COSTS OF CHEMICAL STABILIZATION
(Utilities serving above 50,000, with LSI < -0.5)

Utility Group	Total Population Served (millions)	Number of Utilities	Treatment I (millions of dollars)				Treatment II (millions of dollars)			
			Total Cost	Chemical Cost	Capital Cost	Labor Cost	Total Cost	Chemical Cost	Capital Cost	Labor Cost
1. Survey results: reported losses due to internal corrosion	5.5723	31	1.129	0.492	0.420	0.164	3.624	2.818	0.574	0.166
2. Survey results: no reported losses	23.2745	86	3.369	1.411	1.312	0.493	9.531	7.187	1.663	0.503
3. Supplementary group	23.7614	60	3.032	1.560	1.025	0.330	9.007	7.043	1.454	0.341
Totals	52.6082	177	7.530	3.463	2.757	0.987	22.162	17.048	3.691	1.010

TABLE 3-11

ESTIMATED ANNUAL PER CAPITA COSTS OF STABILIZATION
(dollars)

Utility Group	Treatment I		Treatment II	
	Average Annual Cost per Capita	Range in Per Capita Costs	Avg Annual Cost Per Capita	Range in Per Capita Costs
1. Survey results: reported losses to internal corrosion	0.20	0.06-0.69	0.65	0.08-2.69
2. Survey results: no reported losses	0.14	0.03-0.67	0.41	0.04-2.05
3. Supplementary group	0.13	0.03-0.69	0.38	0.12-1.56
4. Avg for all utilities	0.14	0.03-0.69	0.42	0.04-2.69

TABLE 3-12

COST BREAKDOWN FOR ANNUAL STABILIZATION COSTS
(all utilities)

	Percentage of Total Cost			
	Chemical Costs	Capital Costs	Labor Costs	Maintenance Costs
Treatment I	46.0	36.6	13.1	4.3
Treatment II	76.9	16.6	4.6	1.9

TABLE 3-13

SUMMARY OF ESTIMATED TOTAL NATIONAL COST FOR STABILIZATION[a/]
(millions of dollars)

	Treatment I	Treatment II
Capital expenditures	31.7	42.4
Annual capital cost	2.76	3.64
Annual O & M Cost	4.77	18.47
Annual revenue requirements	7.53	22.16
Population served by impacted utilities (millions)	52.608	52.608
Average annual per capita costs (dollars)	0.14	0.42
Number of utilities impacted (population served greater than 50,000; LSI <-0.5)	177	177

a/ Calculations neglect 92 utilities (serving 7.6 million people) whose water quality could not be characterized.

The total costs of treatment for the utilities can be estimated as the sum of a capital cost and an O&M cost:

$$\text{Annual cost of treatment for missing utilities} = \left(\begin{array}{l}\text{Annual cost}\\ \text{for capital}\\ \text{from Table 3-13}\end{array}\right) \times \frac{\text{(Number of "Missing" utilities)}}{\text{(Number of utilities in Table 3-13)}}$$

$$+ \left(\begin{array}{l}\text{Annual O\&M}\\ \text{cost from}\\ \text{Table 3-13}\end{array}\right) \times \frac{\text{("Missing" population (LSI < -0.5)}}{\text{(Population in Table 3-13)}}$$

Annual capital cost varies far less from utility to utility than does the operating cost. Therefore, the above expression assigns capital cost based on number of utilities and O&M cost based on population.

Simplifying the expression gives (for Treatment I):

$$\text{Annual cost for missing utilities} = \frac{(2.76 \times 10^6) \times \text{(Number of "Missing Utilities with LSI < -0.5)}}{177}$$

$$+ \frac{(4.77 \times 10^6) \times \text{("Missing" population)}}{52.608 \times 10^6}$$

Evaluating the expression for Treatment I gives an annual cost of $1,060,000 (assuming 50% of missing utilities and population have water requiring treatment). A similar analysis gives $2,274,000 for Treatment II. These correspond to average per capita costs of $0.28 for Treatment I and $0.60 for Treatment II for the missing utilities. Note that these costs are much higher than the average annual per capita costs in Table 3-13. The estimates are therefore conservative.

Adding the above estimated costs for the missing utilities to the results given in Table 3-13 yields the results in Table 3-14. Addition of the conservative estimates for the missing population increases the national costs by 14% for Treatment I and 10% for Treatment II. The impact on the annual per capita cost is $0.01 for both treatments.

Therefore, given the assumptions made in the calculation of the costs in Table 3-13, the values there are reasonable estimates of national averages. The addition of missing population should increase total annual

TABLE 3-14

INFLUENCE OF "MISSING" UTILITIES ON COST ESTIMATES

	Treatment I	Treatment II
1. Annual revenue requirements from Table 3-13 (millions of dollars)	7.53	22.16
2. Additional annual cost associated with missing utilities (millions of dollars)	1.06	2.27
3. Total of 1 and 2 (millions of dollars)	8.59	24.43
4. Percent increase	14.1	10.2
5. Total population (including "missing" population) (millions)	56.408	56.408
6. Per capita annual costs (dollars)	0.15	0.43

costs by less than 10-20% and should increase average per capita costs by less than 5-10%.

The sensitivity of the cost estimates to the assumptions made concerning cost of materials, labor and capital also needs to be assessed. Table 3-12 shows the influence of the various factors on total cost. Maintenance is a small fraction of cost and has been estimated conservatively even though it is tied to capital cost. Labor costs are also small, since the treatment processes used require little attention. A near doubling of labor costs would be required to increase total cost of Treatment I roughly 10%. A tripling would be required for a similar influence in Treatment II.

Capital costs, especially for the lime system, have been estimated conservatively. Even so, the cost of Treatment II is relatively insensitive to increased capital costs. Treatment I is sensitive to capital costs and a 30% increase in those costs would raise total Treatment I costs by about 10%.

Both processes are very sensitive to chemical costs. Table 3-15 lists the quantities of chemicals used nationally. As can be seen, the use of either process requires considerable quantities of chemicals. The large increase in chemical costs associated with Treatment II is in large measure due to the greatly increased consumption of CO_2.

Using the values given in Table 3-15, and recognizing that lime is given there as $Ca(OH)_2$, whereas CaO is assumed to be purchased, the impact on costs of an assumed $20.00 per ton transportation cost* can be estimated. Such a cost would increase the chemical costs (cf. Table 3-10) $1.86 million for Treatment I and $7.72 million for Treatment II. These cost increases give 67% and 45% increases in chemical costs and 25% and 39% increases in total costs for Treatments I and II. The total costs for Treatments I and II would become $9.39 million per year and $29.88 million per year. Average per capita annual costs would increase to $0.18 for Treatment I and to $0.57 for Treatment II.

It is therefore apparent that the results are quite sensitive to transportation costs. These costs were not included in the analysis because of the difficulty of estimating haul distances for the large number of utilities involved. Transportation costs may increase the cost of stabilization by as much as 20-30% of the values discussed in this report.

3.5 Benefit-Cost Analysis

As the preceding discussion has shown, internal corrosion causes economic losses in numerous municipal water supply systems. The losses which have been described in this chapter are those of which utilities are

* At $0.07 per ton-mile, this cost allows a utility to be as far away as 300 miles from a source of the chemicals used. This seems to be a conservative estimate.

TABLE 3-15

CHEMICALS USED
(Tons/Year)

	Treatment I	Treatment II
Lime (as $Ca(OH)_2$)		
Surveyed Utilities	45,400	130,000
Supplementary group of utilities	54,100	113,000
Total	99,500	243,000
CO_2		
Surveyed utilities	7,000	110,500
Supplementary group of utilities	700	71,700
Total	7,700	182,200

aware and which they were willing to report on our survey. It is quite likely that internal corrosion causes considerably more damage than that which we have been able to demonstrate. If this damage could be prevented, the utilities involved would experience a financial reward, an annual benefit at least equal to the economic value of internal corrosion avoided. If a utility's distribution system is constructed of high quality materials and the utility is still experiencing internal corrosion losses due to aggressive waters, then the losses should be avoidable by properly stabilizing the water being distributed. The cost of stabilizing the water can be compared with the expected benefit to see if such stabilization is justifiable on economic grounds alone. Even if such a simple weighing of costs and benefits does not provide sufficient justification for chemical stabilization of a water, the potential health impacts of aggressive water in the distribution system may well dictate a need for stabilization.

Not all utilities experiencing losses due to internal corrosion appear to distribute aggressive waters. This could be interpreted in a number of ways. The most obvious explanation is that a portion of the reported losses assigned to internal corrosion are really attributable to replacement due to product aging. In this instance, the piping material has failed at, near, or beyond its projected useful lifetime. Products currently being replaced by utilities probably were designed and specified for a 40-50

year lifetime. Another explanation might be that even so-called non aggressive waters are capable of producing corrosion losses. For such utilities, the relatively simple chemical stabilization considered here is not possible. Certain other utilities with losses of steel, galvanized, or unlined cast iron pipe, and with aggressive water in their distribution system probably need to improve the quality of the materials in the system if internal corrosion is to be avoided. Stabilization of the water will reduce corrosion but should not be considered as the only solution to the internal corrosion problem.

Table 3-16 shows how the utilities who responded to the survey may be categorized in terms of aggressiveness of water distributed, and in terms of losses due to internal corrosion. Four categories are defined by the table. These are:

1. Aggressive water with losses;

2. Aggressive water without losses;

3. Nonaggressive water with losses; and

4. Nonaggressive water without losses.

TABLE 3-16

PLACING UTILITIES IN CATEGORIES
SURVEY RESULTS
(Supplementary results are in parentheses)

	Utilities with LSI $\leq$ -0.5	Utilities with LSI $>$ -0.5	Total
Utilities with losses due to internal corrosion	31 utilities	16 utilities	47
Utilities with no reported losses due to internal corrosion	86 utilities (60)	109 utilities (93)	195 (153)
Total	117 (177)	125 (218)	242 (395)

For Categories 1 and 2, stabilization may be considered and costs for a benefit-cost relation can be found. For Categories 1 and 3, benefits that might be achieved by eliminating internal corrosion can be found. Therefore, a benefit-cost ratio may be found for only Category 1. Costs can be found for Category 2 and benefits can be found for Category 3. Category 4 is irrelevant to the discussion.

Table 3-17 summarizes costs and benefits for Category 1. Internal corrosion of galvanized and steel pipe cannot be eliminated by stabilization and such losses have been separated explicitly in Table 3-17. However, the stabilization of waters corrosive to galvanized and steel pipe should result in the maintenance and possible extension of useful product life. Table 3-18 shows benefit-cost calculations for Category 1 utilities. For the Treatment I approach to stabilization, the benefit-cost ratio is very favorable, being roughly 4. For Treatment II the ratio is somewhat marginal.

TABLE 3-17

UTILITIES WITH REPORTED LOSSES
DUE TO INTERNAL CORROSION
AND WITH LSI ≤ -0.5
(Category 1)

Number of utilities: 31
Total population served: 5,572,300

Annual costs due to losses caused by internal corrosion:	
Total reported	$ 7,267,000
Total pipe replacement	5,004,100
Total "best estimate"	6,613,800
Annual costs due to losses caused by internal corrosion less losses of steel and galvanized pipe:	
Pipe replacements	$ 3,049,600
"Best estimate"	4,307,700
Annual cost of stabilization:	
Treatment I	$ 1,129,200
Treatment II	3,624,000

TABLE 3-18

BENEFIT-COST CALCULATIONS FOR CATEGORY 1

1. Benefits = best estimate of losses less losses of steel/galvanized pipe.

   Cost = Treatment I cost of stabilization.

   $$B/C = \frac{4,307,700}{1,129,200} = 3.8$$

2. Benefits = best estimate of losses less 50% of losses of steel/galvanized pipe

   Cost = Treatment I cost of stabilization.

   $$B/C = \frac{5,460,750}{1,129,200} = 4.8$$

3. As in (1) with Treatment II for stabilization.

   $$B/C = \frac{4,307,700}{3,624,000} = 1.2$$

4. As in (2) with Treatment II for stabilization.

   $$B/C = \frac{5,460,750}{3,624,000} = 1.5$$

Table 3-19 summarizes costs of stabilization for utilities in Category 2. These utilities have reported no losses, so no benefit can be estimated.

For Category 1, the overall economic benefits of stabilization seem very favorable. However, individual utilities may have benefit-cost ratios well above or below the average values given in Table 3-18. For any calculation of this sort, the benefits and costs are not necessarily accruing to the same utilities. A comparison of Tables 3-7 and 3-9 allows B/C values to be found for individual utilities in Category 1. Such a comparison shows a B/C of 37.7 for Utility 19 when Treatment I is used. It also shows a B/C of 0.25 for Utility 8 with Treatment I.

TABLE 3-19

UTILITIES WITH REPORTED LOSSES DUE TO INTERNAL CORROSION AND WITH LSI>-0.5
(Category 2)

Number of utilities: 16
Total population served: 4,765,260

Annual costs due to losses caused by internal corrosion:

Total reported:	$1,032,400
Total pipe replacements:	2,205,400
Total "best estimate":	2,756,000

Annual costs due to losses caused by internal corrosion less losses of steel and galvanized pipe:

Pipe replacements:	$1,854,400
"Best estimate":	2,661,300

In addition to the losses that stabilization might prevent in a water supply system, there is also a possible benefit to be gained in terms of health effect considerations. Chapter 5 discusses health factors related to aggressive waters. While it is not possible to include them in the benefit-cost analysis done here, an awareness that health benefits may be associated with stabilization suggests that these B/C values only provide lower limits for the actual values.

CHAPTER 4

CASE STUDIES

This chapter presents results for four utilities selected to show a range of geographical locations, water quality characteristics, and utility sizes. The utilities are described individually, and a short discussion of their corrosion problems is given along with, where appropriate, how their water might be stabilized to avoid internal corrosion losses.

Table 4-1 characterizes the four utilities by location and size. Table 4-2 describes the character of the finished water of each of the utilities. Table 4-3 shows the nature of the installed pipe for each utility and the annual pipe replacements being made. Table 4-4 describes the chemical treatments being used by the utilities.

The four utilities may be described briefly as follows:

Utility No. 1 - This utility on the West Coast serves 110,000 people. Its finished water is aggressive and has an LSI near -3.0. The utility's distribution system is composed primarily of cast-iron pipe, but with a fair amount of steel included. About 2 miles of 4-in. steel pipe are being replaced annually due to internal corrosion problems. The utility is apparently attempting no corrosion control. While their problem is primarily due to the type of material involved (steel), the utility would probably benefit from a reduced level of aggressiveness of its water.

Utility No. 2 - This large western utility receives its water from several sources. The data in Table 4-2 are for the primary source which provides an aggressive water. This water is treated at the source with lime to reduce internal corrosion problems. The other sources of water are less aggressive, which also helps the overall system's situation. The utility has been practicing corrosion control using lime (to give an LSI $\geq$ 0) for many years and has been able to do away with internal corrosion problems in its aqueduct system. The utility has a distribution system composed of 46% cast-iron, 30% asbestos-cement, and 23% steel. The utility has been experiencing no significant internal corrosion problems in its distribution system. It reports losses due to internal corrosion in its storage facilities.

Utility No. 3 - This small (55,000 population served) northeastern utility distributes an aggressive water which is resulting in a very large amount of pipe replacements due to internal corrosion. The distribution system is 90% cast-iron, 7% ductile, and 3% concrete. Nine miles of 6-in. cast-iron pipe are replaced annually due to internal corrosion losses. The utility does not treat its water and practices no chemical corrosion control. This utility should benefit substantially from a modest stabilization program.

TABLE 4-1

CASE STUDIES - FOUR UTILITIES

	Utility No. 1	Utility No. 2	Utility No. 3	Utility No. 4
Location	Pacific Coast	Pacific Coast	Northeast	South Atlantic
Population Served	110,000	1,050,000	55,000	660,000
Avg Volume of Water Produced (MGD)	10.9	220.0	6.14	72.0
Length of Distribution System (Miles)	275	3,300	115	750
Source of Water	River	Rivers	Purchased	Rivers, Lakes, Wells

TABLE 4-2

AVERAGE QUALITY OF FINISHED WATER

	Utility No. 1	Utility No. 2[a]	Utility No. 3	Utility No. 4
Alkalinity (mg/liter as $CaCO_3$)	10	20	7	45
Total Hardness (mg/liter as $CaCO_3$)	13	24	17	65
TDS (mg/liter)	27	54	33	135
Calcium Concentration (mg/liter)	5	8	5	28
Magnesium Concentration (mg/liter)	1.1	1.0	1.0	3.0
pH	7.0	9.4	6.6	7.2
Temperature				
Maximum (°F)	60.0	72.0	65.0(est)	80.0
Minimum (°F)	48.0	50.0	33.0(est)	35.0
Langlier Saturation Index[b]	-2.9 to -3.0	-0.1 to 0.2	-3.4 to -3.8	-1.1 to -1.7
Aggressiveness Index	9.1	12.0	8.5	10.7
Ryznar Index[b]	12.7 to 13.0	8.9 to 9.6	13.3 to 14.2	9.3 to 10.5

a/ For primary source, which provides 78% of utility's water.
b/ Computed at two temperatures given; other parameters assumed constant.

TABLE 4-3

NATURE OF INSTALLED PIPE

	Steel	Cast-Iron	Asbestos-Cement	Concrete	Plastic	Other
Utility No. 1						
Portion of system which uses material (%)	13	80	2	3	-	2
Amount of pipe of this type replaced annually on avg (miles)	5	0	0	0	-	1
Portion of replacement due only to internal corrosion (%)	50	0	0	0	-	0
Typical pipe diameter (in.)	4	8	8	30	-	?
Utility No. 2						
Portion of system which uses this material (%)	23	46	30	1	+0	-
Amount of pipe of this type replaced annually on avg (miles)	1.2	7.2	0.8	0	0	-
Portion of replacement due only to internal corrosion (%)	0	< 1	0	0	0	-
Typical pipe diameter (in.)	16	6	6	48	6	-

TABLE 4-3 (concluded)

	Steel	Cast-Iron	Asbestos-Cement	Concrete	Plastic	Other
Utility No. 3						
Portion of system which uses this material (%)	-	90	-	3	-	7 (ductile iron)
Amount of pipe of this type replaced annually on avg (miles)	-	9	-	1	-	0
Portion of replacement due only to internal corrosion (%)	-	100	-	100	-	0
Typical pipe diameter (inches)	-	6	-	6	-	12
Utility No. 4						
Portion of system which uses this material (%)	-	89	-	10	1	-
Amount of pipe of this type replaced annually on avg (miles)	-	10	-	2	0	-
Portion of replacement due only to internal corrosion (%)	-	80	-	0	0	-
Typical pipe diameter (inches)	-	6-8 (replaced)	-	16-48	4-12	-

TABLE 4-4

TREATMENT USED AND CHEMICALS ADDED

	Utility No. 1	Utility No. 2	Utility No. 3	Utility No. 4
Treatment				
Sedimentation		X		X
Filtration		X		X
Dual media		X		
Chlorination	X	X		X
Lime for corrosion control		X		
Polyphosphates for corrosion control				X
Chemicals				
Lime		X		X
Alum		X		X
Chlorine	X	X		X
Activated carbon				X
Polyphosphates				X

No Treatment

Utility No. 4 - This large (660,000 population served) South Atlantic utility distributes a moderately aggressive water. Its distribution system is 89% cast-iron and 10% concrete. The utility replaces about 8 miles of 6- to 8-in. diameter cast-iron annually due to internal corrosion problems (tuberculation). The utility has a problem only with unlined cast-iron pipes which are apparently being relined (larger sizes) or replaced. The utility uses polyphosphates for corrosion control and feels that additional stabilization of their water would not reduce internal corrosion losses. Since the water is rather aggressive, further chemical stabilization might still prove useful.

Table 4-5 shows reported costs for the four utilities. Table 4-6 shows water-related corrosion losses and estimated costs of chemically stabilizing their water. Based on these cost data, the following summary may be made for each utility.

Utility No. 1 - This utility experiences substantial ($1.73 per capita) annual losses due to internal corrosion. Assuming that Treatment I (at $0.32 per capita per year) would eliminate 50% of the utility's losses, it would have a benefit-cost ratio of 2.7. Utility No. 1 suffers from a materials problem, but would benefit from stabilization.

Utility No. 2 - Utility No. 2 stabilizes its water and has eliminated substantial losses. It has a $0.04 annual per capita loss due to internal corrosion in its storage facilities.

Utility No. 3 - This utility experiences very large ($20.16 per capita) annual losses. If the utility's own estimate of pipe replacements is used ($100/ft), then the annual per capita cost approaches $100. Stabilization with Treatment I is estimated at $0.68 per capita each year. A benefit-cost ratio of nearly 30 is obtained if such stabilization can eliminate the system's problems. This utility may have materials problems (unlined cast-iron?) but is a prime candidate for a stabilization program.

Utility No. 4 - Corrosion control is currently practiced here, but annual per capita losses due to internal corrosion (tuberculation) are still $1.34. The utility claims that relining is necessary to eliminate their problem. Since stabilization with Treatment I costs $0.07 per capita annually, the utility may still be able to economically reduce some losses by treatment.

Table 4-7 summarizes the overall status of the four utilities. As the table shows, most if not all of the utilities have problems in part because of the state of their distribution system. Two and possibly three of the utilities would benefit from chemical stabilization. The fourth utility already stabilizes its water.

TABLE 4-5

ANNUAL COSTS REPORTED BY UTILITIES

	Utility No. 1	Utility No. 2	Utility No. 3	Utility No. 4
Treatment costs				
Operating cost	4,000	1,260,000	No treatment - Water Purchased	3,039,081
Maintenance cost	1,500	239,000		
Capital replacement cost	1,500	N/A [a/]		48,000 [b/]
Depreciation cost	10,000	545,000		565,000
Distribution costs				
O and M cost	360,000	6,207,000	200,000	1,031,029
Capital replacement cost	350,000	N/A	N/A	16,000 [b/]
Depreciation cost	264,000	4,210,000	-	194,000
Costs for protection from water-related corrosion	0	77,900	0	91,620
Water-related corrosion costs for metering equipment	3,000	0	N/A	0
Water-related corrosion costs for storage facilities	2,200	45,000	No storage facilities	0

a/ N/A = not available.
b/ Excludes $1.2 million for "normal annual additions and replacements."

TABLE 4-6

COSTS OF LOSSES AND ESTIMATED COSTS OF STABILIZATION

	Utility No. 1	Utility No. 2	Utility No. 3	Utility No. 4
Reported annual losses due to internal corrosion	5,200 (meters and storage)	45,000 (storage losses)	5,280,000 (@ $100/ft)	?
Estimated annual costs of pipe replacement (@ $3.50/diam-in.-ft)	184,800 (steel pipe)	-	1,108,800 (cast iron pipe)	887,000 (cast iron pipe)
Best estimate of losses due to internal corrosion	190,000	45,000	1,108,800	887,000
Annual losses per capita (best estimate of losses/population served)	1.73	0.04	20.16	1.34
Estimated annual per capita costs of stabilization of water[a/] :				
Treatment I	0.25-0.32	(already	0.41-0.68	0.05-0.07
Treatment II	0.78-0.80	stabilized)	1.02-1.54	0.06-0.21
Benefit-cost ratio[b/]:				
Treatment I	27[c/]	-	29.6	19.1
Treatment II	1.1[c/]	-	13.1	6.4

a/ Computed for maximum and minimum temperatures, respectively.
b/ Computed using more expensive of two treatment costs.
c/ Assumes 50% of steel pipe losses can be prevented.

TABLE 4-7

DIAGNOSIS OF CASES STUDIED

	Utility No. 1	Utility No. 2	Utility No. 3	Utility No. 4
Aggressive water?	Yes	No	Yes	Yes
Has corrosion control been successfully practiced?	No	Yes (water aggressive before treatment)	No	?
Material problems?	Yes	Yes	?	Yes
Would stabilization be of value?	Yes	Has been shown to be of value	Yes	Possibly

CHAPTER 5

HEALTH EFFECTS OF CORROSIVE WATER

5.1 Introduction and Background

Waters of low pH and/or low mineral content may be corrosive to the pipes used to transport them. These corrosive waters are also sometimes termed "aggressive" due to their action on pipes and equipment, and "soft" due to poor mineral content. It seems plausible that water so damaging to materials such as copper, steel, and asbestos-cement (A/C) pipe could also possess some measurable effects on human populations who use it as the source of drinking water. The medical literature, in fact, contains reports on quite a number of epidemiologic and experimental studies correlating "hardness" and "softness" of drinking water to various health effects. The correlation appears strongest between the presence of cardiovascular disease and use of aggressive-type drinking water. The problem lies in identifying the causal factor(s) present (or absent) in quantities sufficient to produce health effects. As new data are added on the physiological effects of the trace elements present in mineral-rich ("hard") water, some of the correlations can be explained or at least put on a firmer, more testable basis.

This analysis of the apparent correlation between aggressive drinking water and health effects has been greatly assisted by recent comprehensive reviews and symposia: National Academy of Sciences Drinking Water and Health (NAS, 1977) and several reprints and preprints from the U.S. National Committee for Geochemistry.

5.2 Corrosive Water: Limits and Definition

Water is corrosive (soft; aggressive) when it is naturally acidic, or is made so by chemical treatment. Corrosive water also lacks polyvalent metallic ions, principally calcium and magnesium, found in hard or mineral-rich water. Softness and hardness are rather imprecise terms, rooted in the practical concepts of soap requirements for lather formation, and a guide to $CaCO_3$ scale formation in hot water heaters.

The degree of softness is commonly measured by titrating with a chelating agent and is expressed as an equivalent concentration of calcium carbonate. Soft waters range from 0 to 75 mg/liter $CaCO_3$ equivalents, while very hard waters commonly titrate over 300 mg/liter.

Schroeder and Kramer (1974) suggest the use of LSI in studies of water corrosiveness instead of the terms soft and hard. Two federal panels

on water quality (NAS, 1974; NTAC, 1968) have also recommended against use of these terms and suggest the inclusion of specific ion concentrations. This procedure would avoid confusion in future studies but is not helpful in evaluating previous efforts.

The pH of natural waters is a measure of acid-base equilibrium achieved by the various dissolved compounds, salts and gases. The principal system regulating pH in natural waters is the carbonate system which is composed of carbon dioxide (CO_2), carbonic acid (H_2CO_3), bicarbonate ion (HCO_3^-), and carbonate ions ($CO_3^=$). The interactions and kinetics of this system have been described by Stumm and Morgan (1970). The usual pH range of domestic water supplies is 5 to 9, with mineral-rich hard water at the base end and corrosive, soft water at the acid side. The pH of a water is not related to its buffering capacity.

The pH of corrosive water appears to be related to its potential health effects. For example, Stiff (1971) suggests that if cupric ions were the toxic form of copper, while copper carbonate complexes were relatively nontoxic, then the increased toxicity of copper in soft waters can be explained by the pH difference rather than the amount of copper. In addition, highly acidic waters in contact with storage equipment, distribution system piping, and the consumer's home plumbing, will leach solutes, adding a profile of metals with other potential health effects (Delfino and Lee, 1971; Jones, 1964).

5.3 Potential Mechanisms: Health Effects of Corrosive Water

The presence (and in some cases, selective absence) of trace elements is the most likely source of an effect on health from corrosive water. If trace elements are related to human disorders, they can be considered in two categories: (a) as micronutrients, and (b) as accumulating environmental contaminants. Homeostatic mechanisms undoubtedly exist for micronutrients as they do for bulk elements, conserving with inadequate intake and excreting excesses. The entire area has only recently begun to be studied, however, and little is known about chronic dose-response effects. Accumulation and interaction of trace elements over many years could influence a variety of diseases. Such interaction might be discovered only through epidemiologic study of large areas and large populations.

In general, three types of health-related effects could be postulated in connection with drinking water:

1. Deficiencies of essential elements through inadequate intake in the cases where water furnishes either a significant proportion of the element or a small amount in highly absorbable form compared to dietary sources.

2. Excesses of essent l microelements could occur, accumulating by failure of homeostatic mechanisms, large dietary intakes, increased absorption or decreased excretion. During aging, shifts in essential metallic content of organs occur (Schroeder, 1965).

3. Disorders may occur from chronic intake of trace metals for which there are poor homeostatic mechanisms and accumulation/synergistic effects over a long period of time, or overt toxicity.

The effects of trace elements on health have been much more difficult to identify when compared to vitamin effects, for example. The elements have roles in body physiology as cofactors, coenzymes, or, interchangeably, to furnish an ionic charge necessary to push an enzymatic reaction to completion. These reactions, vital to good health, are nevertheless difficult to pin down to specific health-related reactions and a specific element. To further tie a source (nondietary, water-supplied elements) to the health effect is to complicate an already-difficult study. Therefore, if the chemical character of consumed water is to be related to specific diseases, the analytical data on water quality and content must be above reproach. For many of the studies, high level quality control of water quality data was not practiced. This weakens conclusions made using that information.

5.3.1 Deficiencies of essential elements in corrosive water: No deficiency disease is known to occur naturally for domestic animals or humans who drink from water sources that are low-mineral and corrosive. On the other hand, no intensive effort has been made to detect such deficiencies in man or animals; therefore, deficiencies in a marginal form cannot be excluded.

The metals perform functions vital to life. Inadequate intake may impair cellular and physiologic function and even cause illness. On the other hand, other elements present in low concentrations may interfere with vital functions. It is of great interest to this particular study to see if there is enough of any inorganic element present in normal finished water (as drunk by man) to furnish a significant amount as compared to amounts required (excreted and presumably taken in as food). If normal water contains a significant amount of a trace element that corrosive water lacks, it is a real target area for health effect study. A tabulation is presented (Table 5-1) from several sources, including a summary from the NAS review on Drinking Water and Health (1977).

The trace elements' presence in food as compared to water supplies has been tested and tabulated. There is, on analysis, considerably higher levels of all of the elements found in dietary products as compared to finished drinking water; the availability of the compounds from the two sources, however, has only been touched upon (NAS, 1977).

TABLE 5-1

HUMAN REQUIREMENTS FOR TRACE ELEMENTS AND AMOUNTS OCCURRING IN FINISHED WATER

Element[a]	Daily Requirement[b]	Avg. Amt. in 1 Day's Drinking Water (2 ℓ)[c]	2 ℓ Measured[e]
Cadmium	15-35 µg	0.6-24 µg	3.0 µg
Calcium	800 mg	9-144 mg	-
Cobalt	70-80 µg (est.)	0.2-58 µg	4.0 µg
Copper	2 mg	26 µg-2.1 mg	0.270 mg
Chromium	0.02-0.5 mg	0.015-0.058 mg	0.005 mg
Iron	10-20 mg	0.14-3.8 mg	0.440 mg
Lithium	5 mg (est.)	0.1 mg-1.3 mg	-
Magnesium	300 mg	1.6-100.0 mg	-
Manganese	7-25 mg (est.)	0.051-0.9 mg	0.044 mg
Molybdenum	500 µg (est.)	172-2,048 µg	-
Nickel	48 µg (est.)	8-112 µg	10 µg
Selenium	1.5-33 µg (est.)	< 10 µg	-
Vanadium	May not be required	0-80 µg[d]	-
Zinc	15 mg	0.16-4.02 mg	0.290 mg

a/ Limited to elements with major quantitative differences in hard versus corrosive water.

b/ Recommended Dietary Allowances, 8th ed., National Academy of Sciences, 1974; or, estimated from body content and excretory data if no MDR exists.

c/ Mean of 100 cites, U.S.A., National Research Council data.

d/ Detected in ~4% of samples (Kopp and Kroner, 1967).

e/ Measurement: McCabe (1969).

For drinking water studies, an advantage is gained from the food marketing practices in the United States, whic.. bring fruit and vegetables from Florida and California, beef from Texas, flour from Kansas, etc. This helps cancel out food-related mineral differences except for dietary-deprived groups such as the poor and aged, and emphasized any water-related effects that may occur.

In contrast to food supplies' national or worldwide origin, drinking water is essentially a local product, that is, it is normally consumed a reasonable distance from its source. This is eminently true where the consumption of untreated well waters is common practice, as in rural areas.

The usual parameter considered when looking at the health effects of corrosive water is the potential hazard from the constituents of the corrosive water that have been leached out of house pipes, the delivery system, etc. It must also be considered that some of the naturally occurring minerals that are present in hard water could be responsible for a beneficial effect on health. The list of essential minerals and trace elements increases every year or so. For those elements which are necessary, toxicity may occur with the lack as well as the excess. Then the diet is a poor source, or when the trace metal in food is poorly available when eaten, water becomes the primary source. Table 5-1 lists the percentage of each element that is calculated to be furnished by water.

Corrosive, soft water is poor in metal content, furnishing excesses only when it leaches them out of the environment. In addition, certain water treatment processes, such as "lime-softening," remove the following ions from water:

Iron

Nickel

Cobalt

Cadmium

Lead

Zinc

Copper

Treated or finished water, as it is discharged from treatment plants, thus contains low levels of these elements. A potential health effect related to water softening is the removal of zinc, an essential trace element that modern diets often lack in sufficient quantity.

Absorption of all trace metals is regulated at the intestinal mucosa of the small intestine. Excretion is also predominantly through the gut, chromium being a conspicuous exception. Schelling et al. (1973) have studied the availability of zinc from the diet, and have shown that ingestion of zinc with a meal retards its absorption by humans. Unlike the trace elements found in water, the metals in grain products, for example, are strongly complexed as a result of the high phytate and fiber concentrations (O'Dell et al., 1972; Reinhold, 1972). Trace metal deficiencies may occur despite high intakes in the foodstuffs making up the diet (Reinhold, 1975). Such poor availability from the diet makes the highly available elements present in drinking water much more important to health.

Other elements used by the body which are usually deficient in corrosive water are listed in Table 5-2. Table 5-3, following, shows the wide range of solutes measured in drinking water. Corrosive water, mineral deficient at the source, is responsible for some of the very high values in Table 5-3, which includes tap samples.

The pathways to pathology lie in many interrelated cycles, all with cellular and enzymatic control or feedback mechanisms. Many of the trace elements present in drinking water are vital coenzymes in normal (and pathological) pathways. Those elements of the same valence often substitute for one another when there is a large imbalance in intake. The effects of such interaction on the complex cycles regulating cardiovascular health are probably negligible on an acute basis. There is no experimental information available on potential effects of chronic trace element imbalance.

The cause-effect relationship between specific trace elements and cardiovascular pathology has not been established. There are solid bases for hypotheses, but these are still being tested, in the long-term collection of epidemiological data. Without this foundation, testable hypotheses cannot be formulated regarding health effects of specific elements leached from the environment by corrosive water. This question, however, may be asked: are there likely physiologic pathways to cardiovascular pathology through which solutes found in aggressive drinking water could act? The answer is a qualified "yes."

5.3.2 The corrosive water-cardiovascular disease association: Certain trace elements present in drinking water (or food) have been correlated with the presence of cardiovascular disease for over two decades. The correlation of trace element concentration in diseased tissue with a disease process does not, however, establish a cause-effect relationship unless supported by additional data. For example, the loss of nickel from the myocardium after acute infarction, and its increase in the plasma is well recognized as a consequence of infarction, not necessarily a cause.

TABLE 5-2

MINERALS/CONSTITUENTS PRESENT IN NORMAL WATER, LACKING IN CORROSIVE WATER[a]

Ammonia-nitrogen	Chromium
Barium	Cobalt
Beryllium	Magnesium[b]
Bicarbonate ion	Nitrate
Boron	Potassium
Cadmium	Phosphorus
Calcium[b]	Silver
Carbonate ion	Sodium
Chloride	Sulfate
	Vanedium

a/ Significant at the 99.5 level of confidence, $p < 0.005$.

b/ Bulk ions notably lacking in corrosive waters. From 8th Ann. Report, Council on Environmental Quality (1977).

TABLE 5-3

OTHER TRACE ELEMENTS IN DRINKING WATER WITH POSSIBLE HEALTH EFFECTS

Element	Range (µg/ℓ)	Average (µg/ℓ)
Barium	2-340	43
Beryllium	0.01-1.22	0.19
Cadmium	1-120	9.5
Chromium	1-112	9.7
Cobalt	1-48	17
Copper	20-860	40
Lead	2-140	23
Manganese	0.3-3,230	59
Mercury	0-2	None
Molybdenum	2-1,500	68
Nickel	1-130	19
Silver	0.1-38	2.6
Vanadium	2-300	40
Zinc	2-1,183	64

Note: Adapted from NAS, 1977.

However, some associations of cardiovascular disease with trace element metabolism have been suggested in the medical literature. In addition, some of the bulk ions are closely related to the healthy function of the cardiovascular system by affecting fluid balance, electrical transmission, membrane phenomena, and energy metabolism in general. Long-term exposure of experimental animals to increased cadmium results in hypertension. This is a solid basis for the hypothesis that excessive cadmium intake may be one causative factor for hypertension in man. It follows that corrosive waters, which leach these trace elements from their environment, would contribute directly to producing such pathologies.

In many, an early effect of cardiovascular disease is narrowing of resistance vessels, either by deposits or by contraction of the blood vessel musculature. The initial arteriolar narrowing, if continued chronically, becomes permanent by several mechanisms (intimal thickening, muscular coat hypertrophy, arteriolar necrosis, hyaline degeneration). The chronic effects of these cardiovascular effects occur bodywide: kidney, heart, brain, retina. Coronary and cerebral artery atherosclerosis, myocardial infarction, "malignant" hypertension and cerebral thrombosis/hemorrhage are common sequelae.

The Council on Environmental Quality (CEQ), in their 1977 report, used Environmental Protection Agency (EPA) monitoring data (146 counties which use surface water) to study heart disease relationships to bacteria and 16 chemicals in the water before treatment. Numbers of white males and females who died of cardiovascular diseases in 1968 to 1972 were correlated with the hardness of the drinking water supply in the county where they died. Negative correlation coefficients indicate that as the hardness of the water increased, deaths decreased. Negative signs were found for both males and females for the following: acute and chronic ischemic heart disease, and cerebrovascular disease. In addition negative correlations between water hardness and disease were seen for white males with aortic aneurysm and "other arterial" disease. Table 5-4 lists the major studies linking corrosive water to cardiovascular disease, and the statistical significance of their findings.

Rheumatic heart disease and congenital heart/circulatory system disease (neither of which would be expected to have environmental involvement) were not significantly correlated with water hardness in either sex.

Although the link between softness of water and the statistical probability of increased risk of cardiovascular death has been seen repeatedly, a medical rationale for cardiovascular pathology based on water softness is difficult to make. Most of the more recent research has emphasized the solutes--trace elements and bulk ions--present in mineralized or hard water that might have a beneficial effect on cardiovascular health. A few studies have attempted correlations between the high levels of minerals present at the tap (not at the source) in corrosive water. These elements, to fit mortality data, would be deleterious to cardiovascular health. One of the better analyses was presented by Schroeder and Kraemer (1974), who found that

TABLE 5-4

EPIDEMIOLOGY STUDIES DEMONSTRATING HIGHER DEATH RATE IN AREAS WITH CORROSIVE, "SOFT" FINISHED PUBLIC DRINKING WATER

Geographical Unit Studied	Arteriosclerotic Heart Disease (Positive Correlation with Corrosive Drinking Water	Author, Year of Publication
USA by state	Positive; $p = 0.01$	Schroeder, 1960
USA, cities	Positive; $p = 0.01$	Schroeder, 1960
USA by state	Positive; $p < 0.01$	Schroeder, 1966
USA, cities	Positive; $p < 0.01$	Schroeder, 1966
USA, "economic areas"	Positive; $p = 0.01$	Sauer, 1970
UK, County boroughs	Positive; $p = 0.01$	Morris, 1961
UK, County boroughs	Positive; $p < 0.01$	Crawford, 1968
Sweden, towns	Positive but $p > 0.05$	Biorck, 1965
Ireland, urban areas	Positive but $p > 0.05$	Mulcahy, 1966
Canada, provinces	Positive; $p = 0.05$ (CVA only)	Neri et al., 1972
Canada, municipalities	Positive; $p = 0.05$ (CVA only)	Neri, et al., 1972
USA, Okalhoma counties	No correlation	Lindeman, 1964
USA, Colorado counties	Positive but $p \geq 0.5$	Morton, 1971
Japan	Positive	Kobayashi, 1957 (Anal. by Schroeder, 1961)

corrosiveness of water (LSI) was directly correlated with deaths from heart disease at high levels of significance. They calculated three parameters on which they based the importance of the solute in water:

1. Does solute occurrence correlate with death rates from cardiovascular disease?

2. Is the solute readily absorbable from water?

3. Is the solute in quantities sufficient to produce an effect?

Schroeder and Kraemer (1974) suggested that an increment to the diet of 5% or less of any element from water "would probably not make the difference between health and disease." In addition, the authors eliminated specific conductance, dissolved solids, alkali metals and the anions found in water as unlikely parameters to be involved in cardiovascular disease. The six elements that Schroeder and Kraemer thought might be involved in the protective effects of hard water are:

Barium	Calcium
Strontium	Magnesium
Silicon	Boron

Table 5-5 lists several other elements which have levels (measured in drinking water) which can be correlated with the presence of cardiovascular disease in different geographical areas.

5.3.3 Noncardiovascular health effects of corrosive water: Cardiovascular disease is the general health umbrella under which most epidemiological correlations of pathology and drinking water are made. The earliest discovery of the relation between mortality and drinking water was that of Kobayashi, who observed that areas in Japan with high stroke mortality had very corrosive (soft, acid) river water (Kobayashi, 1957). When Schroeder and Kraemer (1974) demonstrated a soft water-arterioscherotic disease correlation in the United States, they also attempted to correlate water corrosiveness with other pathologies. Constituents of drinking water were much less significantly correlated with other diseases or with congenital malformations. In England and Wales, the changes in cardiovascular death rates seen with changes in water hardness (increases in deaths with softer water) were not seen for noncardiovascular death rates (Crawford et al., 1971). It appears, therefore, that the most robust epidemiological link between disease and corrosive water is that of cardiovascular disease. Nevertheless, a recent report implicates a cancer link.

TABLE 5-5

POSTULATED MECHANISMS OF HEALTH EFFECTS IN ELEMENTS WITH DIFFERING LEVELS IN CORROSIVE VERSUS HARD WATER

Element	Occurrence	Authors	Health Significance
Cadmium	Occurs in soft tap water exposed to galvanized pipes at 10 μg/ℓ.	Schroeder, 1967 Lener and Bibr, 1971 Perry, 1973	Highly correlated to cardiovascular mortality when found in milk. Cadmium dosage produces hypertension in rats.
Chromium	Occurs in hard (mineral rich) waters.	NAS, 1977	Has possible beneficial cardiovascular effects; deficiency elevates serum glucose and cholesterol.
Copper	Liver levels of copper higher in soft water cities. Corrosive water left standing in copper pipes can accumulate 1 ppm (potentially a sizable fraction of daily ingestion).	NAS, 1977	High Cu levels in water positively correlated with cardiovascular mortality.
Lithium	Found predominantly in hard water.	Voors, 1969	Negatively correlates with cardiovascular mortality; e.g., may be "protective?" Has effects on catecholamines, and (suggested) influence on coronary prone human behavior.
Vanadium	Found predominantly in hard water.	NAS, 1974	Negatively correlated to mortality from cardiovascular disease; inhibits hepatic cholesterol biosynthesis.

TABLE 5-5 (Concluded)

Element	Occurrence	Authors	Health Significance
Zinc	Corrosive and hard water contain similar amounts due to leaching or pipe corrosion by the soft water, and highest natural levels in raw hard water. Zinc in water may furnish significant intake due to crops grown in zinc-poor soils.	Sandstead, 1976	Positive but weak correlation with cardiovascular mortality.
Calcium/ magnesium	In areas with corrosive (soft) water, serum Ca and Mg found low in man (USA) and low in bone in UK. Myocardial muscle Mg low in Canada corrosive soft water city.	Bierenbaum et al., 1973 Neri et al., 1974 Crawford and Crawford, 1969	Decreased Magnesium causes Ca deposits in arteries.
Selenium	Found predominantly in hard water.	Tappel, 1974	Essential cofactor of enzyme important in fatty acid metabolism.

Cornhill and Burton (1978) have made a statistical survey of the 99 largest U.S. cities, and find that cities with soft water (low number of dissolved solids) have a significantly higher cancer rate. The specific ions found in cities with hard water that correlated with the protective effect included calcium and magnesium (both also positively correlating with the "protective" effect in cardiovascular disease) and also sodium and chloride. Details of the methods, epidemiological detail, and analysis were not presented in this cited report.

The epidemiological evidence indicates that the presence of some other bulk solutes normally found in hard water (which could incidentally be removed by water treatment) are linked with cancer protection. Dallaire (1977) suggested that more accurate record keeping is needed (epidemiological studies) along with development of more reliable analytical methods to monitor chemicals in water.

Two reports (Comstock, 1971; Bierenbaum, 1973) have considered the possibility that the cardiovascular risk associated with drinking corrosive/soft water may relate to a difference in smoking patterns. In a British study, middle aged men drinking soft water at home were more likely to smoke cigarettes. Bierenbaum's single report does not find such a correlation in the U.S. cities he studied, but since smoking has high correlation to cardiovascular disease risk, the suggestion is worthy of further consideration. It is interesting to speculate whether dissolved minerals in drinking water could affect "taste" of cigarettes, lessening their use in mineral-rich water areas. As an example, taste abnormalities which occur in some disease states have implicated clinical zinc deficiency (Davies et al., 1968; Henkin 1971).

5.3.4 "Beneficial" elements in mineral-rich, hard water: A few of the more commonly studied trace elements and bulk ions are discussed individually in the following section. Emphasis lies on the rationale for their effect on health when they are present in drinking water. These elements are commonly lacking from corrosive water in that they do not occur in nature in soft water and are not leached from the environment. The following elements are discussed:

Calcium	Magnesium
Chromium	Manganese
Lithium	Vanadium

5.3.4.1 Calcium: In general, the literature is strangely lacking on hypotheses and rationales for any beneficial effects of calcium in hard drinking water, which would be lacking in corrosive water supplies.

The calcium in drinking water (even the highest levels known) would be of minor input compared to the calcium intake from a normal diet, if both were of equal absorptive properties. It is always possible, of course, that waterborne calcium is more absorbable than dietary calcium.

One major pathway by which calcium in water could affect cardiovascular health is through its action on zinc binding. Zinc has widespread effects on other trace metals and in animal experiments has been shown to affect cholesterol levels and elastin and collagen in arterial walls (Jacob et al., 1977; Allen and Klevay, 1978). Calcium facilitates the formation of insoluble zinc complexes, greatly reducing zinc absorption.

High levels of calcium intake may be protective to cardiobascular disease by another route. Albanese et al. (1973) have shown that supplementation of human diets with calcium decreases the serum concentration of cholesterol.

Neri et al. (1975) have cited studies by which calcium is said to block absorption of both cadmium and lead, two elements which have been frequently correlated with the soft water-toxicity data. Conversely, of course, cadmium has been shown to inhibit the absorption of calcium, and the body is forced to mobilize calcium from bone. This mobilization also releases zinc and another cycle of trace metal interactions occurs (Hurley and Tao, 1972).

5.3.4.2 Chromium: According to the NAS Water Study, chromium is one of the more likely elements in water to be protective from cardiovascular disease. A study by Hambridge (1971) was cited to indicate that atherosclerosis can be induced in animals by chromium-deficient diets. Rats studies by other authors (Schroeder and Balassa, 1965; Schroeder, 1966) found that low chromium diet increased the incidence of aortic plaques. Adding chromium to the diet also lowered serum cholesterol levels in male rats.

Chromium occurs in several valence forms, with the trivalent and hexavalent forms most common in biological systems. Although hexavalent chromium is considered toxic, trivalent chromium is usally considered to be innocuous and even a trace element essential for human health. Absorbable chromium is poorly available from food sources, and trivalent chromium

absorption is inhibited by ingestion with foodstuffs. Drinking water is said to supply an appreciable amount of absorbable chromium (Schroeder et al., 1962). Geographical differences in possible signs of chromium deficiency have been attributed to different levels in drinking water (Hopkins et al., 1965), although Mertz (1967) suggests that the interchange and competition between related metals makes actual chromium deficiency hard if not impossible to define, especially in human populations. According to NAS (1977), low levels of chromium have been shown to occur in populations that exhibit increased serum glucose, increased cholesterol levels, and which have greater incidence of aortic plaques.

One of the transition elements with known biological function, trivalent chromium tends to hydrolyze in aqueous solution and to form polynuclear complexes. This process can lead, in a biological situation, to the formation of macromolecules. Alkaline media (such as those found in hard water areas) promote these polynuclear chain formations. Mertz (1967) suggests that small changes in the degree of this complexation are quite important for biological activity. In the hexavalent state, chromium has acidic properties, does not form coordination compounds, but (unlike the trivalent form) it penetrates the erythrocyte membrane easily and becomes firmly bound to hemoglobin.

5.3.4.3 Lithium: Voors (1969) reviewed the beneficial effects of the trace element lithium upon five factors in cardiovascular disease, and suggested that the correlation between cardiovascular disease and soft water could be partly explained by soft water's low lithium content. Using a graphic presentation, Voors correlated the arterioscherotic heart disease mortality for white males in 100 U.S. cities with lithium content and water hardness. There is a good correlation, but the relationship needs to be more firmly established. Voors (1969) suggests several potential mechanisms by which lithium could be acting against the known risk factors of arteriosclerosis or other cardiovascular disease. One of the more interesting hypotheses was that of reducing the "stress factor" in so-called "type-A behavior," the competitive, always-pressed-for-time behavior that is frequently associated with coronary heart disease.

Lithium is therapeutically useful for manic patients, and has been shown effective in anti-agressive behavior in Siamese fighting fish and other animal studies.

The mechanisms of lithium action appear to lie in its function on the nerve cell transmitters, the catecholamines. The transmitter involved in sympathetic, or stress-related, activity, norepinephrine, is profoundly affected by lithium in animal experiments, both in blocking release of this transmitter in the brain, and in facilitating re-uptake once the transmitter is released. Lithium affects the transmitter serotonin (5-HT) in experimental animals by activity on an enzyme, tryptophan hydroxylase (Mandell

and Knapp, 1977). There is additionally a great deal of indirect evidence that for a variety of animals lithium may play a role as a co-factor in some neural biochemical processes.

There is an indication (Schou, 1957) that lithium is not stored well in the body (4 mg/day in the diet and 3 mg/kg found in tissue). Voors (1969) in addition suggests that drinking water may be the chief source of lithium, and that the lithium levels of such water may be deficient locally. The trace element is not at this time considered essential, but of the 14 trace elements now considered necessary for man, five have been added in the last 7 years (Coulston and Mrak, 1977). There is a rationale for a role of lithium in human nutrition. Intentional intake has been shown to be beneficial to at least some humans. Lithium levels tend to be lower in soft water, correlating with occurrence of cardiovascular disease. The trace element must certainly be considered as a possible candidate for contributing to this epidemiologic finding.

5.3.4.4 Magnesium: Magnesium is an essential element for man, and the minimum intake should be over 200 mg/day. Although magnesium is present in many nuts, legumes, and meats, the water supply, according to the NAS "should not be overlooked as a significant source of magnesium (NAS, 1977). Corrosive, low pH, soft water, however, is a very poor source of this mineral.

Magnesium is one of the best examples of an element that is present in mineral-rich, hard water, low in corrosive acid waters, and which may have health effects by its absence.

Magnesium deficiency may result from excess sweating, particularly if the water supply is low in magnesium. Consolazio et al. (1963) exposed men to high temperature for several days and recovered 10 to 15% of the total body output of magnesium in sweat. Absorption of magnesium takes place in man in the small intestine, and persons with intestinal malabsorption would also be vulnerable to deficiency of the mineral. Magnesium is conserved by the body which resorbs it from the renal tubules during kidney clearance. Persons with early renal disease often have defective resorptive mechanisms and lose much magnesium. In addition, depletion of magnesium is likely to occur as a result of diuretic therapy; Wacker (1961) and others have documented increased urinary losses of magnesium with thiazide and mercurial diuretics.

Alcoholics, both those with high blood alcohol and those in the withdrawal state, have been found to have low levels of magnesium (Mendelson et al., 1969). It is suggested that this is due not only to inadequate intake, but to increased excretion of magnesium in urine and feces. Excessive fecal loss of magnesium may also occur in nonalcoholic subjects following large amounts of oral calcium supplementation because of competition for a common transport system in the intestine. An infant, after prolonged diarrhea, suffered convulsions associated with a low plasma magnesium (Savage and McAdam, 1967).

Magnesium function in man: Magnesium is the most abundant intracellular divalent cation in both plants and animals. It has been recognized for 50 years as an activator for important enzyme systems, including those using adenosine triphosphate (ATP). Since ATP is required in the energy processes of nerve inpulse generation, muscle contraction, protein, fat, and nucleic acid synthesis and virtually all important biochemical processes, the function of magnesium is very basic to the health of the organism. Wacker et al. (1962) report that clinical magnesium deficiency may be characterized by a variety of signs including muscular tremor, mild neurologic signs, a low-voltage T-wave in the electrocardiogram, and tetany. Durlach (1967) has proposed blood-related manifestations of clinical magnesium deficiency, including phlebothromobosis, and Caddell (1967) reported a positive response to magnesium supplementation in Nigerian children with symptoms of neuromuscular irritability, and electrocardiographic changes (short PR interval and flattened-to-inverted lateral precordial T-waves).

Neri et al. (1975) reports that magnesium has the greatest difference between subject dying from myocardial infarct and accident cases, a difference that is present in both soft- and hard-water areas. The hearts of healthy residents in hard-water areas also contain more magnesium than those in soft-water areas. On this basis, Neri concluded that low magnesium levels are responsible for the cardiovascular disease-corrosive drinking water associations.

5.3.4.5 Manganese: This essential trace element is present in over half the tested water supplies in the United States in concentrations ranging from under 1 to 3,250 μg/liter. The average daily consumption of manganese by man is 3,000 to 7,000 μg (NAS, 1977), mostly in nuts, tea, and spices. Hard water, therefore, could supply a significant proportion of the daily intake.

The divalent manganese is a coenzyme in many mitochondrial reactions, specifically steps in carbohydrate breakdown. Succinic dehydrogenase has an absolute requirement for manganese. Deficiency of the element has been documented in many mammals but human hazards of low manganese have not been studied. Manganese is widely distributed in the body after oral ingestion of the two oxidation states that normally occur in water (Mn^{+2} and Mn^{+4}); the divalent is absorbed faster. Metabolism of the element is regulated by the adrenals.

Manganese is not accumulated in the body; the NAS reports that livers of humans of all ages contain 6 to 8 ppm manganese. Organic manganese is excreted by both urine and feces.

Oral manganese is very low in toxicity; rats can tolerate 2,000 ppm in food and doses under 4,800 ppm had no ill effects on chickens (Matrone, 1977). A human case of well-water contamination with very high levels of manganese produced an encephalitis-like disease with high muscle

tone, rigidity and tremors. The general effect was somewhat like the extrapyramidal disease of Parkinsonism.

Manganese interacts with several elements of vital importance to the health of the blood vessels and the cardiovascular system in general.

Manganese is essential for the health of the pancreatic islet tissue, so the element is vital to glucose metabolism. A diabetes-mellitus-like syndrome can be produced in guinea pigs with manganese deficiency (Everson et al., 1959). Impaired glucose tolerance is usually accompanied by hypertriglyceridemia and hypercholesterolemia. It is possible to formulate a rationale, then, for the effect of manganese on the cardiovascular system through lipid metabolism which is a well known risk factor to man.

5.3.4.6 Vanadium: This element is one of several with positive correlations when metal concentrations in water and cardiovascular health are compared.

Vanadium, in its lower valence forms, is poorly absorbed. As far as is known, the trace element is nonessential to man. It is excreted by several species of experimental animal and man in the urine, and it is not stored or accumulated in the body.

Most water does not have detectable amounts of vanadium; 3.4% of the samples of Kopp and Kroner (1967) contained the element, in concentrations ranging from 2 to 300 μg/liter.

Vanadium can probably be eliminated from consideration as an element responsible for the cardiovascular disease-corrosive water link because of its low percent occurrence in water supplies, its low toxicity and apparently nonessential nature in human metabolism.

5.3.5 Deleterious effects of certain elements in drinking water: The 1977 NAS review on drinking water and health selected a few elements that are more suspect than others in contributing to the deleterious health effects geographically correlated with corrosive water. The elements, cadmium, copper, lead, and zinc are all correlated in different ways with cardiovascular health patterns. These are discussed individually. Beryllium, correlated with cardiovascular effects by other studies, is also added.

5.3.5.1 Beryllium: Beryllium is a trace element with toxic potential found in excess only in highly acid waters. About 30 years ago, workers exposed to beryllium powder in fluorescent light manufacture developed berylliosis, with symptoms of chemically induced pneumonitis. In water, however, beryllium is rapidly adsorbed to surfaces, especially at neutral or higher pH. It is highly unlikely, therefore, that waterborne beryllium would be a source of any adverse effects on humans, even from areas with acid tap water.

5.3.5.2 Cadmium: The EPA Interim Primary Drinking Water Standard for cadmium was set at 10 μg/day (1975 data) and this amount is known to be found when aggressive tap water is exposed to galvanized pipes (Schroeder et al., 1966).

Cadmium has been shown to depress electrical events of the heart, characterized by slowed conduction through the AV node and seen on the electrocardiogram as a prolonged PR interval and extended QS interval. Kopp et al. (1978) gave long-term low level (5 ppm) dietary cadmium to rats to look at specific effects. They found that long-term low level exposure to cadmium did indeed produce cardiac effects, either by obstructing conduction or altering cell excitability.

Hill et al. (1963) studied the interactions of trace metals in the arterial wall, and noted that increased intakes of cadmium in experimental animals cause histologic abnormalities that resemble those of copper deficiency. Cadmium appears to interfere with the copper mediated crosslinking of elastin (Hill et al., 1967) and collagen (Chou et al., 1969) in the aorta.

Cadmium, zinc, and copper also interact in the liver, kidney, and intestine. The health effects are potentially those of the inhibition of calcium absorption and possibly cholesterol metabolism, but the mechanisms are poorly defined (Larsson and Piscator, 1971).

A low intake of cadmium (5 ppm) will induce sodium retention in rats, which increases blood pressure, when dosed over a long period of time (Schroeder and Vinton, 1962; Perry and Erlanger, 1974).

5.3.5.3 Copper: Copper, an essential element to man, is a component of several vital enzymes and its intake is essential. The normal intake is about 2.5 mg, but only a third of that is actually absorbed and part of that third is excreted. NAS (1977) estimated a net of 0.13 mg would be absorbed with a 2.5 mg intake in man.

There is no shortage of copper intake in the USA. It is probably the excess that has the greater potential of effect on human health. Copper is a gastrointestinal tract irritant and can be highly toxic. (Sheep are especially sensitive to copper toxicity and are thus poor models for human copper effects.) A human infant died from drinking water that contained 6.75 mg/liter copper for 14 months (Walker et al., 1973) and a 1.0 g quantity of copper sulfate was used successfully for a suicide (Chuttani et al., 1965). The NAS review (1977) reports several cases of human toxicity resulting from drinking beverages kept in copper with copper doses ranging about 40 to 50 mg.

A few humans, particularly those with low glucose-6-phosphate dehydrogenase enzyme levels, show toxic effects with quite small levels of copper intake. There is also a metabolic disorder of copper metabolism, Wilson's disease, which leads to brain and liver damage and death in a few years from excess body copper. There is some concern that a substantially large intake of copper can convert the borderline or inactive disease to an active form. Contact of soft, low pH (corrosive) water with copper piping could raise the intake of copper by as much as 1,400 µg/day, whereas drinking hard water could reduce the intake (Schroeder et al., 1966). This is because copper salts (the sulfates and chlorides) are highly soluble in low pH water, but in mineral rich, noncorrosive water, there is CO_2 present and copper is often precipitated as carbonate. Actual samples of the water from Seattle, for example, known to be highly corrosive, increased in copper content after standing overnight in house pipes by as much as 1.978 mg/liter (Dangel, 1975).

5.3.5.4 Lead: In animal models, lead toxicity is much greater in corrosive water than in hard water. In a 96-hr LD_{50} study in two species of fish, for example, 5.6 and 23.8 ppm lead were lethal in corrosive water: the same fish took the same time to die in hard water only when lead concentration was increased to 482 and 442 ppm (Pickering and Henderson, 1965).

Humans are said to be in soft tissue lead balance, excreting as much as they take in (Kehoe, 1961). Neri's study of the heart tissue of myocardial infarct victims in soft and hard water areas, however, showed a definite difference: 0.1 ppm lead in heart muscle where hard water was used but 0.18 ppm lead in the heart muscle of victims who used soft water (Neri et al., 1975). Gross et al. (1975) also reported that bone lead increases with age.

NAS (1977) averaged out a great deal of lead analysis data and concluded that the average drinking water lead concentration was 13 µg/liter, or, about one-tenth that amount furnished by a normal diet. In areas with corrosive water, however, the addition of large amounts of lead may occur in household plumbing and in the water distribution system. Karalekas et al. (1975) found as much as 1,510 µg/liter in Boston drinking water (average 30 µg/liter) and Dangel (1975) measured an increase of 34 µg/liter lead in the corrosive Seattle water which remained in household pipes overnight.

No benefits to man of lead intake are known. The potential and real health effects of chronic high lead intake in drinking water are not known. What is known has been recently reviewed (NAS, 1977; Zielhuis, 1975). Very young children, it appears, are under greater risk of toxicity due to lead, and people with marginal zinc intakes may also be at risk of health effects due to the high lead levels seen in corrosive drinking water which remains in contact with solder or lead pipes.

5.3.5.5 Zinc: The required mineral zinc is actually toxic to aquatic life when dissolved in corrosive (soft) water. Cairns and Scheier (1968) studied the lethal dose to bluegill fish (Lepomis macrochirus) and found that as little as 1.9 mg/liter killed the fish in soft water whereas 12.5 mg/liter was required for the same effect in mineral-rich (hard) water. Long standing of corrosive water in galvanized pipes has raised the zinc concentration to 40 mg/liter which level is toxic to fish.

In human health, there is no evidence that zinc contributes to human toxicity by an excess in water, but rather the problem lies in marginal or deficient zinc intake. Nutritional surveys have not shown diets to be grossly zinc deficient in the United States, although it is hypothesized that large segments of the population have a marginally zinc-deficient diet (NAS, 1977) especially since persons with sickle cell disease have an increased loss of zinc in their urine.

The zinc requirements of man, 10 to 15 mg/day, could be furnished at least two-thirds by hard drinking water. As mentioned in other discussions of trace elements, it is found that food sources, high in a metal by analysis, are in fact poor sources of the element in the body because of interaction with other food constituents. Zinc chloride and zinc sulfate are very soluble in water. In hard water with considerable bicarbonates and other anions, the solubility of zinc is a function of the zinc carbonate and zinc hydroxide, soluble in water (25°C) at 10.7 and 0.2 mg/liter, respectively.

Zinc interacts with other trace elements and Sandstead (1976) and others (NAS, 1977) have suggested that the zinc:copper or zinc:cadmium ratio of metal intake are quite important to health. If a ratio (rather than total quantities) is the important factor in zinc metabolism or utilization, the excess zinc leached into corrosive water from galvanized pipes is of no benefit, even to zinc-deficient populations. Only the naturally mineral-rich or hard waters would contain dissolved elements in a usable ratio. This important theory, as yet unstudied and untested, could be of vital importance to the input of drinking water on human health.

5.3.6 Presence and potential health effects of asbestos in drinking water

5.3.6.1 Background: Excessive or prolonged inhalation of asbestos dust is known to cause pulmonary fibrosis (asbestosis), lung cancer (almost exclusively in the case of cigarette smokers), and pleural and peritoneal mesothelioma. An increased incidence of gastrointestinal (GI) cancers also has been reported in some occupational groups, and there is suggestive evidence of an excess of larygeal cancers. Reported increases of the latter cancers are small in comparison to increases in incidence of pulmonary carcinoma and mesothelioma.

Inhalation exposures to asbestos necessarily constitute ingestion exposures since the bulk (90% or more) of the fibers which enter the tracheobronchial tree ultimately are moved upward by mucociliary action, and then swallowed or expectorated. The cilia that perform this function are greatly reduced in number and activity in the heavy cigarette smoker. The heavy smoker will therefore expectorate and swallow fewer fibers.

Selikoff and his co-workers (1972, 1974) have done several epidemiology studies on the health effects of asbestos in insulation and factory workers. Overall, Selikoff found the incidence of GI cancer in asbestos workers to be two to three times the level in the general population. This effect is more evident after 20 years or more from first exposure. One group for example (Selikoff et al., 1972) was composed of 623 persons who worked with asbestos in 1943. This study measured their death rate through 1971. Cancer of the digestive system caused 41 deaths where 13 were expected. A second study looked at 877 workers who were employed in an asbestos plant between 1941 and 1945. Twenty-six deaths had occurred by 1971 due to cancer of the GI tract where 13 were expected. A third study examined the cause of death in 17,800 asbestos insulation workers in the United States and Canada between 1967 and 1971. Fifty-five deaths were attributed to GI cancer where 27 were expected.

A number of occupational cohorts have not shown an excess of deaths attributable to gastrointestinal cancer, notably those reported by Meurman et al., (1974) and Newhouse et al. (1972). However, when examined in aggregate, the data justifies the presumption that in occupational exposures a relationship between inhaled (physiologically ingested) asbestos and GI cancer does exist, and that it is probably dose-related, that is, the largest excess occurs in the most heavily exposed.

5.3.6.2 Occurrence in drinking water: The presence of asbestos bearing rock formations throughout the U.S. accounts for its presence in both source and treated waters. Millette (1979) has reported that of 365 cities or water supplies analyzed for asbestos, 45% were reported to have significant concentrations in them. No data are available to assess whether the presence of naturally-occurring asbestos in water is in any way related to the occurrence of naturally aggressive or soft waters.

Asbestos-cement (A/C) pipe is used widely throughout the U.S. for the conveyance of potable water. It has been established that corrosive (low pH and/or low hardness) waters may attack the cementitious matrix of A/C pipe, and release asbestos to the water conveyed through it. The leaching action is not a classic one, as in the case of lead leached from customer service piping. The potential toxicant itself (asbestos) is not leached, but is mechanically released when its binder dissolves.

A mathematical index to estimate the corrosion potential of various waters to A/C pipe has been developed, and is discussed in detail on

Pages 8-9. When aggressive (i.e., corrosive) water passes through A/C pipe, the pH and calcium content of the water increases, and concomitantly, the AI.

The U.S. Environmental Protection Agency (EPA) has conducted several laboratory and field experiments to determine whether A/C pipe would be attacked (and asbestos fibers released) under various conditions of water quality. While much of the work is still in progress, the preliminary results suggest that "highly aggressive" waters (AI < 10.0, LSI < -2) and certain "moderately aggressive" waters will attack A/C pipe.

In areas of aggressive water, the asbestos exposures may range from 1 million to over 100 million fibers per liter depending on length of pipe and flow rate. Millette et al. (1979), did not analyze the health effects, but did note that the large majority of U.S. water consumers are not exposed to concentration of asbestos fibers above 1 million fibers per liter.

Another recent review by Commins (1979) on asbestos in drinking water reviewed the environmental exposures to asbestos and found a wide range of asbestos in water supply, from less than 0.1 million to 2,190 million fibers per liter of water. Typical tap water in Canada and the United States contained between 0.3 million and about 3 million fibers per liter. Measurements within the United Kingdom also gave results within that range. The report concluded that A/C pipes in general do not appear to contribute much to the level of asbestos in water.

5.3.6.3 Potential health effects: The most important environmental health question concerns whether or not chronic exposure to ingested asbestos could cause cancer of the GI tract. Can ingested asbestos fibers penetrate the GI tract and migrate?

The issue of fiber penetration of the mucosa has been a very controversial one. The research of Westlake et al. (1965, 1974), Hallenbeck and Hesse (1967) and Cunningham et al. (1977), suggested that penetration was plausible, but never unequivocally confirmed the phenomenon. More recently, Storeygard and Brown (1978) examined specimens of the jejunal mucosa injected with amosite asbestos, and observed penetration of the epithelial cells. A review by Hallenbeck and Patel-Mandlik (1978) studied orally administered chrysotile asbestos fibers and found that in the newborn the fibers left the GI tract and were found in the kidney, liver, spleen, heart, and other organs. Cook and Olson (1979) reported the appearance of asbestos-like fibers in the urine of human subjects who ingested drinking water containing these fibers. Cook concluded that the observations provide direct evidence for penetration of the gastrointestinal mucosa.

Several studies have addressed whether or not ingested asbestos adversely affects GI tract functions. Jacobs et al. (1977), fed rats asbestos

for 10 months and reported an increase in the enzyme levels of the small intestinal lining.

While all these studies are of considerable theoretical interest, the practical question is not whether fibers penetrate the mucosa and are distributed in the body, but whether any harm results.

5.3.6.4 Animal studies: A large number of feeding studies employing a variety of test animals and asbestos fiber types, have been conducted in an attempt to elucidate any ingested asbestos - GI cancer relationship. Bonser and Clayson (1967), Smith et al. (1965, 1973), Webster (1974), Gross (1974) and Bolton and Davis (1976) studied animals fed diets containing between 0.27% and 6% asbestos without evidence of increased tumor production.

Two studies have reported finding malignant tumors when animals were allowed to orally ingest asbestos (Gibel, et al., 1976; and Wagner, et al., 1977). Gibel's work fed both talc and asbestos to rats and showed that asbestos added to the diet caused GI tumors considerably more often than talc in the diet. The dose fed to the rats was equivalent fo 25 mg asbestos ingested per kilo body weight. For man, this would be nearly 2 g of asbestos per person. Compared to some of the highest levels of asbestos known in tap water, that would equal 173 x 10^6 fibers per liter, equivalent to about 0.2 mg per liter. Even at such high level of fiber occurrence in water, man would need to drink 10^7 liters of water to get that dose. An 80-year-old who has drunk 2 liters a day for his entire life has ingested less than 10^5 liters.

In the other (Wagner) study, the doses were less but still high; 100 mg of chrysotile asbestos for 5 days a week, for 6 months. It is interesting that the chrysotile-fed rats on an average, lived 5 days longer than animals given talc, although the tests did indicate that asbestos can produce a small number of malignant tumors in animals. Asbestos, however, did not appear to be highly carcinogenic in view of the high dose level given to the rats in this experiment.

The National Institute of Environmental Health Sciences (NIEHS) and EPA are attempting to assess the carcinogenic effects of ingested asbestos in a lifetime study involving rats and hamsters. Chrysotile and amosite asbestos is being fed at a 0.1% level in a pelleted rodent diet. EPA recently reported that the length of life of the exposed hamsters has not been reduced from cancerous tumors. However, histopathology studies must be completed before any firm conclusions can be drawn.

5.3.6.5 Epidemiology studies: No evidence of excess mortality was found in the study of a population living in an area of naturally occurring asbestos deposits in the United States (Fears, 1976). Levy et al. (1976) studied the epidemiology of cancer death in Duluth, Minnesota, which at the tap contains between 1 and 30 million amphibole asbestos fibers per liter.

Levy et al. measured the GI cancer incidence 14 years after the start of this asbestos contamination and found no pattern which could be construed as an association between asbestos in the water and tumor incidence.

Harrington et al. (1978), have investigated the use of A/C pipes for public water supply in Connecticut over the years 1935 to 1973 and have looked at the cancer incidence data for GI cancer. Their study compared towns with A/C pipe and towns without A/C pipe. This epidemiologic investigation, which is still continuing, was designed to determine whether or not cancer incidence differs between groups receiving water through asbestos-cement pipe as opposed to other pipe systems. Subject age, amount of piping, and aggressiveness of water were all controlled. There is to date no excess in cancer of stomach, colon or any part of the GI tract for the period 1935 to 1973 in populations receiving water through asbestos-cement piping. There was no trend which indicates any relationship between GI cancer and the use of A/C pipe. In fact, the 1965 to 1973 trend was toward lower observed-to-expected ratios in towns with A/C pipe.

A study of 22 Canadian municipalities with high concentrations of naturally occurring asbestos in their water supplies failed to reveal any excess gastrointestinal cancer which could be attributed to asbestos consumed in drinking water (Wigle, 1977).

A retrospective epidemiology study (Kanarek, 1978) in the San Francisco Bay Area, where drinking water has high levels of naturally occurring asbestos, reported a statistically significant relationship between ingested asbestos and the incidence of certain cancers. Census tracts were grouped from low to high asbestos in water values, and then compared with corresponding cancer statistics from the state tumor registry. The ratio of "observed" to "expected" cancer in white female digestive-related organs among those exposed to low levels of asbestos compared to those exposed to high levels was 1.4. Like the epidemiology studies of soft-water cardiovascular disease relationships, the experimental design can only suggest an association, not pinpoint causation. Kanarek pointed out that data on important variables such as cigarette smoking, alcohol consumption, dietary factors, occupational history, and population mobility were not available for proper controls.

Severson (1979), has studied the effects of asbestos in drinking water on cancer incidence in the Puget Sound region. This study is particularly interesting because it covers the area of Seattle where aggressive water is known to exist. Severson suggested that the study showed only relationships since it was an indirect study. He concluded that the negative findings seem to indicate that imbibed asbestos is not related to alimentary tract cancer. Like the Kanarek (1978) epidemiology study, this work also did not control for smoking history, dietary factors, and alcohol consumption. The conclusion also stated that if there were a strong dose-response relationship between imbibed asbestos and cancer, one would not have expected to obtain the results that he did. A major self-criticism of the Severson report

is that the asbestos was measured in the river water and not at the tap. The amount of asbestos that might be dissolved from A/C pipes by the aggressive Puget Sound Water is not reflected by measuring asbestos fibers in the river water and comparing one river watershed to another.

5.3.6.6 Summary: In summary, a thorough review of the literature indicates that although inhaled asbestos has been recognized as a human health hazard, there is no firm evidence that people who ingest asbestos from drinking water are at risk from short- or long-term health effects. Disregarding naturally occurring asbestos, the presence or levels of asbestos in the drinking water are a function of the aggressiveness of the water conveyed through asbestos-cement pipe.

Conclusions on human effects of ingested asbestos will need to wait for very long-term case control epidemiological studies, some of which have begun. Better methodology in sampling water supplies for asbestos fibers, and more animal tests will provide a better assessment of the health implications of ingested asbestos in drinking water.

5.4 Animal Effects: Corrosive Waters

There have been large numbers of experimental animal studies on health effects of the trace elements found in drinking water. The effects of bulk elements under the umbrella of water hardness has had little good research reported.

5.4.1 Health effects, water hardness studies: Puschner et al. (1969) watered two groups of 10 pigs from the normally mineral-rich Munich water supply but removed the minerals from the water of one group by ion exchange (304 ppm down to 2 ppm). No differences in arteriosclerosis or serum cholesterol in the swine were reported.

A higher degree of arteriosclerosis in corrosive water areas has been reported in swine in two other studies, however. Bijlenja et al. (1967) reported observations on aortas of 1,637 swine raised in 12 locations in the United States and Europe. Atherosclerosis scores of pigs raised in corrosive water locations were more than twice those of animals from hard water areas. The Pig Industry Development Authority of Great Britain reported about the same time that more pigs from soft water areas had evidence of atherosclerosis in the abdominal aorta than those from the hard water region (Howard et al., 1967).

Neal and Neal (1962) watered four groups of rabbits (nine per group) with solutions of varying hardness: (a) distilled water, (2) naturally hard water, (c) distilled water plus calcium carbonate, and (4) distilled water plus magnesium sulfate. Rabbits on distilled water were reported as developing the most atherosclerosis, and those given magnesium sulfate developed none at all. These data, showing cardiovascular effects when distilled

rather than corrosive or soft drinking water was used, weakens the hypothesis that a toxicant occurs in corrosive water, and strengthens the hypothesis that an element found in mineral-rich or hard water produces some beneficial health effect.

Hartung (1973) reviewed the toxicity of trace elements to aquatic species when the medium was soft versus hard water. Although most of this work was done using lethal, acute effects in static bioassays, some chronic measurement has been done. (See Table 5-6.)

TABLE 5-6

TOXICITY OF TRACE ELEMENTS IN CORROSIVE VERSUS HARD WATER
LC_{50} (ACUTE BIOASSAY)

Element	Dose Lethal to 50% of Fish[a]/96 hr: Corrosive Water (ppm)	Hard Water (ppm)	Author
Chromium (Cr^{+6})	5.07-7.46	67.4-71.9	Pickering and Henderson (1965)
Lead	5.58-23.8	442-482	Pickering and Henderson (1965)
Zinc	1.9-3.6	10.1-12.5	Cairns and Scheier (1968)

a/ P. promelas (fathead minnow) and L. macrochirus (bluegill).

5.4.2 Toxicity to animals from soft waters: Schroeder (1965) has indicated that copper is more toxic in soft water than in hard water to crustacea, molluscs, insects, and zooplankton. McKee and Wolf (1963) report that zinc is four times as toxic to snails in soft as in hard water. Cadmium and lead have recognized toxicity and are known to be leached from pipes. Copper correlates positively with cardiovascular disease and, in North America, was found more often in aggressive (soft) water analyses than in hard water. (This is also true for manganese and zinc, but it is unlikely that these essential trace elements have harmful physiologic effects.) The low calcium levels of aggressive waters increase the absorption of a number of trace metals by aquatic animals. The toxicity of a number of these trace metals, therefore, is increased in aggressive water (Schroeder, 1965; Hartung, 1973). The data of two other authors on the toxicity of trace elements in corrosive water are tabulated in Table 5-6.

The 1974 National Academy of Sciences study reports calculations demonstrating the increased toxicity to fish of ions dissolved in corrosive as compared to hard water. The 40-hr LC_{50} was measured for rainbow trout, and both copper and zinc were approximately four times more toxic in soft water ($CaCO_3$ equivalent of 10 mg/liter) as in moderately hard water ($CaCO_3$ equivalent 100 mg/liter) (NAS, 1974).

5.4.3 Water pH as a factor in animal toxicity: Several studies on fish and other aquatic organisms have been run. A representative study, defining lower pH health effect limits in fish is described. Corrosive, soft water is low pH water.

Mount (1973) performed bioassays on the fathead minnow (Pimephales promelas) for a 13-month, one generation time period to determine chronic pH effects. Tests were run at pH levels of 4.5, 5.2, 5.9, 6.6, and a control of 7.5. At the two lowest pH values (4.5 and 5.2) behavior was abnormal and the fish were deformed. At pH values less than 6.6, egg production and egg hatchability were reduced when compared with the control. It was concluded that a pH of 6.6 was marginal for vital life functions.

In man also, pH has been a factor in water toxicity. Many incidences of metal toxicity have been reported connected with the pH of the water supply and the type of storage or distribution system utilized. Smith and Blomfield (1973) reported the case history of a 14-month old child in Australia that exhibited evidence of Wilson's disease. Because of the severity of the case, the possibility of copper poisoning was investigated. The family had moved to the farm in question when the mother was four months pregnant. An investigation of the drinking water, which came from a well and passed through copper pipes in the house, indicated that the water pH of 4.4 gave a copper concentration of 675 µg/liter in the cold-water supply. The child in question subsequently died, and elevated copper levels were found in his liver. Gallery et al. (1973) traced the history of a patient on home dialysis who suffered acute nausea, vomiting, and fever which was found to be caused by zinc concentration of 625 µg/liter contained in the home water supply. The water had been stored in a galvanized tank.

Alkaline, mineral-rich water keeps metal ions as metallic hydroxides and carbonates. It is known that many of the more toxic metals possess a chemical form in corrosive water that is highly absorbable, compared to their form in hard water. This means that the pH difference alone could account for the increased toxicity of some metals in corrosive water.

5.5 Health Effects: Corrosive Water on Man

Many of the larger studies on the health effects of corrosive water on man have been discussed earlier as the mechanisms of such health

effects regarding the individual trace elements were discussed. The significance and validity of all these studies are worthy of further consideration, however. For example, there is the very real problem, here and in all epidemiological studies, of the identity of the controls.

5.5.1 Epidemiologic problems with correlations and cause-effect hypotheses

5.5.1.1 Statistical considerations: The question asked of the studies here is whether or not drinking corrosive water has an effect on health. Most of the cited studies make correlations by using correlation coefficients to measure associations rather than the coefficient of regression of some disease parameter upon the water factor (corrosiveness). A regression coefficient is influenced only by variation in the independent variable (corrosiveness), whereas a correlation coefficient can be affected by chance variation in cardiovascular disease incidence. Furthermore, the commonly used correlation coefficient allows no assessment of the magnitude of an effect, and good correlation is possible even if change in the independent variable produces no dependent variable change.

5.5.1.2 Design considerations: The populations in a study relating health to corrosive water are of great importance and have not been given proper consideration in some studies.

When "disease risk" uses mortality data, and does not adjust the rates of death, data are included on frequencies of death from unrelated causes, and among a mixture of population subgroups. Many papers reviewed by MRI failed to adjust for even the simplest population subgroups: age, sex, and race. On some occasions the age ranges are very large, which makes the assumption that no important variations in death rate due to age occurs.

The number of studies that take corrosiveness data from city water supply information may be in error, especially if it was measured at the treatment plant rather than the consumers' taps. Further, there appears to be virtually no information on (or compensation for) "point of use" devices, such as "water softeners." It is unlikely in cities with corrosive water that home "water softeners" are used, because this water is mineral-deficient to begin with. Misclassification is more likely when people are assumed to be drinking hard water, and in reality they use demineralized water. One study, for example (Comstock, unpublished information) noted that one-sixth of the population of Southern California drank bottled water (usually mineral-rich). Schroeder and Kraemer (1974) report that soft drinks, account for 360 ml of the daily intake which they estimate varies from 1,000 to 2,000 ml.

The improper use of, or lack of, experimental controls in most studies published to date impairs the ability to draw a clear "cause and effect" relationship between corrosive water and health effects. What is the proper control for a drinking water study? Some work has used mineral levels in the heart muscle of cardiovascular disease victims, as other cases use the mineral levels in heart muscle of accident victims (from the same geographical area) as the control. Mortality data without laboratory measurements present infinitely more problems in the choice of a control or baseline population.

5.5.1.3 Potential confounding factors in a corrosive water - human disease correlation: Many demographic, socioeconomic, and cultural characteristics vary with location. Since corrosiveness of water also varies with location, it is possible that some studies are measuring the correlation of cardiovascular mortality not with water, but some other parameter. In fact, this entire review operates on the assumption that the cause for the corrosive water health effect is not known. Since some good studies have controlled for demographic characteristics, however, it is more probable that the health effect is related to water, and the unknown parameter is a characteristic or constituent of water.

Nevertheless, despite these reservations on epidemiologic correlations in general, impressive correlations can be made time and time again between the protective effect of mineral-rich, hard water on humans from mortality due to cardiovascular disease.

5.5.2 Corrosive water as related to human health problems in the United States

Chronologically, the earliest studies linking death rates from heart disease to a pattern of geographic locality were by Enterline and Stewart (1956). These authors, using death rates in the United States from 1949 to 1951, reported that place of residence might be a major risk factor in death from cardiovascular disease. They did not link corrosive drinking water to this high death rate, but did rule out migration patterns, availability of medical care, and inaccurate death counts as potential causes of the relationship. Some characteristic of drinking water was an obvious suspect.

Over the last few years, the work of Sauer and others have frequently confirmed that there are geographic cardiovascular disease patterns (Sauer and Enterline, 1959; Enterline et al., 1960; Sauer, 1962; Chase, 1963; Sauer et al., 1966; Kuller et al., 1969; and Sauer and Parke, 1974).

Kobayashi (1957) first published strong data linking corrosive drinking water to a geographical patterns in death rates. Noting that all

river water in Japan is soft, and some of it highly acidic, he presented an excellent association between death rates from apoplexy in Japan and the quality of the drinking water. Other authors reviewing his data found corrosive water closely associated with high death rates from all cardiovascular-related disease.

Schroeder's large studies on U.S. populations have confirmed a link of drinking water quality and disease. Because corrosiveness per se is not a parameter that is widely available from published water quality data, and since simple mineral content or softness is widely available, Schroeder's correlations have featured water softness and cardiovascular disease. Schroeder (1960a; 1960b) looked at detailed water quality information for 163 U.S. metropolitan areas. In these early studies he found soft water highly associated with deaths from coronary heart disease in white males ages 45 to 64. Magnesium and calcium-rich waters (hard water) were found in metropolitan areas with the lowest coronary heart disease death rates. On a state-by-state basis and less detailed water quality information, Schroeder still found soft water significantly more prevalent in areas with high death rates from both coronary heart disease specifically and all cardiovascular diseases in general.

In later efforts, Schroeder (1966) and Schroeder and Kraemer (1974) repeated the above studies, using data from 201 metropolitan areas and, separately, from 88 cities. The variables were broken down further: age, sex, and race were separated out of the data pools and arteriosclerosis, hypertension, and stroke divided from cardiovascular disease into specific entities. These refinements did little to pinpoint any specific group that was more highly at risk, but they again found significantly high mortality rates from cardiovascular disease (especially in white males 45 to 64) in cities with soft water.

Other national studies showing that mineral-deficient or soft water correlates significantly with heart disease: Dudley et al. (1969); Masironi (1970); Winton and McCabe (1970); Voors (1971), the many studies of Sauer, cited above, and Hudson and Gilcreas (1976). There is a federal study currently under way, sponsored by agencies dealing with both water quality and heart disease. Dudley et al. (1969) studied 116 metropolitan areas nationwide; Voors looked at 99 cities and Hudson and Gilcreas collected data from 96 metropolitan areas. Winton and McCabe limited their study to 135 central counties with well-defined water sources. Masironi reported on data from 42 states. Tabulation of such varied data give a false impression of uniformity; there were great differences in statistical treatment, age groups, and choice of cardiovascular pathology studies. The impressive fact is that they all correlate mineral-deficient, soft drinking water with an increased death rate from cardiovascular disease in populations who drink that water.

Smaller, state/local studies have also correlated the risks of cardiovascular disease with corrosive or soft water usage. In general, these studies do not show as robust a correlation as the national studies in the United States.

Omaha, Nebraska, with mineral content (hardness) of 154 ppm and Winston-Salem, North Carolina with only 30 ppm (soft water) were compared. Two different groups, looking at the same data, come up with different conclusions on cardiovascular disease risk in the two cities. There are many confounding factors, including a heavy use of home water softeners in Omaha and well-water use instead of city water in Winston-Salem (Bierenbaun et al., 1973).

A 1964 study of water softness and cardiovascular disease mortality rates in Oklahoma reported no associations. Subsequent analysis, limiting the data base to 38 counties where at least half the population used public water supplies, showed a positive correlation between water softness and cardiovascular disease deaths in white males aged 45 to 64 years (Lindemann and Assenzo, 1964).

Individuals over the entire state of Massachusetts have a high risk of cardiovascular disease (Massachusetts Public Health, 1975). In studies of the 23 largest cities in the state, all water was found to be extremely low in mineral content or soft (only 6 to 49 ppm). Three hard water communities in the Los Angeles area (82, 189, and 327 ppm hardness) did not differ in cardiovascular mortality rates (Allwright et al., 1974). Washington County, Maryland, has a wide range of water types and two good studies have been done there. Comstock (1971) measured tap water of persons dying from arteriosclerotic heart disease as well as tap water of controls drawn from the same general population (412 males aged 45 to 64). The risk of using soft tap water (of under 150 ppm hardness) was significant. A doctoral thesis (Schreiber, 1976) used the same population, also found a risk of soft water in the home, but the statistical significance of the data was negligible.

Kansas City Kansas, and Kansas City, Missouri, use water from the same river, both considered hard by most criteria. Kansas City, Missouri, however, artifically softens the water to 78 ppm, whereas Kansas City, Kansas, uses mineral-rich unsoftened water, 189 ppm. There is no statistically significant difference in cardiovascular-renal mortality between the cities, however, The study (Bierenbaum et al., 1975) did not take into account either sex or race, both of which are important.

There have been no studies showing that corrosive water is protective or beneficial when ingested over long periods of time. There have been, however, studies that go against the general trend when softness or hardness only are considered. Tyroler, for example (Kessler and Levin,

1970) reported on death rates from arteriosclerotic and degenerative heart disease among white males aged 55 to 64 years in North Carolina. Death rates were lowest in very soft water (23 ppm) areas but also highest in moderately soft water areas (51 to 61 ppm). Klusman and Sauer presented a paper (Freedman, 1975) that suggested no correlation existed between cardiovascular-renal death rates (males aged 35 to 74) and the calcium-magnesium content of a county's water. All counties in Indiana were studied.

The Canadian studies of Neri and associates have a very large sample size on which to base correlations between drinking water constituents and disease. Neri has analyzed the micronutrients present in hard and soft water (Neri et al., 1975) for correlations with cardiovascular disease. The data bases contain several measures, including water analysis of 575 Canadian communities, where drinking water was sampled at the tap and analyzed for hardness and elemental content.

Data were also included on analysis of seven elements in heart muscle of patients dying from cardiovascular disease. Tissue from hearts of people who died in accidents were included as controls, and these were assumed to be representative of "healthy" individuals.

Neri found zinc, chromium, lead, and copper either at identical levels in the two tissue groups or at levels inconsistent with the physiological data. Calcium and cadmium are identical in healthy tissue in soft and hard water cities, although tissue from myocardial patients have higher-than-control levels of these elements. Magnesium has the greatest difference in values between control and experimental tissue; this occurred in populations from both hard and soft water areas. Therefore, based on the tissue analysis data, magnesium has the highest probability of being responsible for the association between high cardiovascular mortality and aggressive, drinking water.

Elements found in Canadian tap water were also scrutinized to find those responsible for the apparent aggressive water-cardiovascular disease association. Elements in the drinking water were eliminated or included in Neri's intercorrelational analysis by the following format:

<u>Eliminate</u> from consideration elements that:

1. Are highly exhangeable or inter-reactive in the body, because discrimination of individual element effects is not possible.

2. Are rarely present in measurable quantity.

3. Are present but unrelated to aggressive to mineral-rich (soft-to-hard) gradient.

4. Are present in drinking water at levels negligible when compared to those levels ingested from other sources.

5. Are uncorrelated with either cardiovascular mortality or mortality in general, although showing a soft-to-hard water gradient in quantity.

From the elements remaining, select for:

1. Elements with physiological role in cardiovascular disease (or in another postulated disease effect).

2. Elements required at levels so that the normal diet would provide no safety margin.

Neri suggests that magnesium or secondly, lithium, best fulfills his elimination and acceptance criteria.

In review, his weakest premise eliminates elements that are present in drinking water at levels far below food levels. The form in which some of these elements exist in water may make them more absorbable than when they are found in food. The presence of fiber and other food forms are known to profoundly influence the absorption of some trace elements.

Sharrett and Feinleib (1975), epidemiologists from the National Heart and Lung Institute, reviewed the correlations between corrosive-type drinking water and local cardiovascular mortality rates. Without adding data of their own, they took a fresh and critical view of the 49 studies from nine countries.

Suggestions were included in their paper for further research or in-depth analysis of existing data. The main points:

1. A primary responsibility of authors exists to distinguish between the hypothesis that water exerts its effects through agents contained in it and the hypothesis that water is an index of some other geographical factor.

2. More work should deal with drinking water at the tap rather than at the water treatment area.

3. The relationships between rainfall and the local water should be untangled.

4. Since major national studies (but not all regional studies) consistently show correlations between corrosive waters and cardiovascular disease, further analysis or more data-gathering should seek associations from other regionally distributed factors.

Sharrett and Feinleib (1975) review several other studies. Zinc and copper are in high levels in acid tap water (aggressive water), probably because of leaching from galvanized and copper pipes. Iron and manganese are also found at higher levels in acid water. Neri et al. (1974) in Canada found copper highest in aggressive water.

Cadmium and zinc are equal in non aggressive and aggressive waters. Lead is highest in the aggressive water, but variable. Chromium, molybdenum and nickel appeared equal in both. In biological organisms, the bioaccumulation of cadmium and zinc appear to be more related to the characteristic of the species (metallothionein levels, for example) and sediment bound levels than they do to actual water levels of the metals; there were often no reported differences in zinc and cadmium levels as a function of measured water hardness or pH. Engel and Fowler reported, however, that the toxicity of cadmium increases as the salinity of water increases (Engel, D.W. and B. A. Fowler (1979)).

Most (all?) researchers in studies showing higher death rates from cardiovascular disease in areas with low pH, mineral-poor waters take their water quality data at the treatment plant. Water consumers, however, may receive a water substantially modified by materials in the distribution system. Sharrett and Feinleib (1975) suggest that the following water mineral changes are likely to occur during distribution:

No change: calcium

magnesium

lithium

vanadium

but the following are changed as much by distribution as by the source:

copper

iron

lead

zinc

The NAS (1977) summarized the elements most likely to be involved in drinking water and epidemiologic health effects. The list is quite similar to Feinleib's above.

Crawford and Clayton (1973) found high levels of lead in the bones of persons autopsied from aggressive water-towns compared to hard-water towns

in the United Kingdom. They noted that until recently, over 90% of the homes in large industrial towns in Britain had lead pipes. This could indicate a high level of leaching from pipes in towns that distribute corrosive water. If the pipes were galvanized or copper, cadmium could be leached out.

Masironi (1970) looked at raw river water and Sauer (1970) also at raw water measures and found the correlations with cardiovascular deaths more significant than when data on finished water were used. Sharrett and Feinleib (1975) suggest this may indicate that water is merely representative of something else in the geochemical environment. It is noted, however, that drinking water quality had the greatest effect on mortality in hotter parts of the United States (where people drink more water) (Dudley et al., 1969).

Schroeder (1966) took the death rates of caucasians for 1960 of persons who died of the major cardiovascular diseases. These rates were compared with the average hardness of treated municipal water supplies by state. In addition, cities with published information about mortalities for coronary heart disease in white males 45 to 64 years of age were compared with cities whose municipal supplies had been analyzed for trace elements and major other constituents in finished water. There were 88 cities which had these data. Analyses of tap water from private dwellings was not considered in this study.

Statistics used by Schroeder involved correlation of cardiovascular disease and water hardness. The degree of significance of coefficients of correlation were obtained from standard table; the statistical significance by the t-test. Inverse correlations were consistently found.

Water associated with high death rates was soft; it had low magnesium, sodium, potassium, sulfate, and barium, but more copper. The waters were not significantly different in pH in high and low cardiovascular mortality areas.

Perhaps one of the best studies (which hopefully will answer many questions) is only now in progress. A study of the relationship of cardiovascular disease and trace elements in drinking water is presently being conducted by EPA and National Heart, Lung, and Blood Institute (NHLBI), and no published summaries of data were found. Data are being gathered by collection of one-time "grab samples" of water from the kitchen tap along with extensive health examination surveys of 4,200 randomly selected individuals from 35 geographically distributed areas. pH, conductivity, and inorganic analysis will be made on the tap water samples, and, in addition 12 monthly samples are being collected from the water utilities in each study area. Data collection was planned to be complete in 1975, when analysis and compilation of the information would begin. Only preliminary data have been presented at meetings to date.

5.6 Summary

In the United States, mortality from certain chronic diseases, particularly cardiovascular disease, hypertension and stroke, is associated with various water characteristics related to corrosiveness. Hypotheses suggest a protective action of some elements found in hard water, or harmful effects attributed to elements associated with soft or corrosive water. The hypothetically protective agents include calcium, magnesium, vanadium, lithium, chromium, and manganese. The hypothetically harmful agents include cadmium, lead, and copper, all of which tend to be found in higher concentration in soft water as a result of its relative corrosiveness. The statistical correlations between these factors and disease, however, are not conclusive, and the agents responsible for the correlations often do not include elements listed above. The hypothesized causative agents have been derived from the study of mortality rates in different geographical areas with different chemical characteristics of drinking water. Autopsy studies have also been performed, comparing tissue levels of minerals that are increased in soft water with subject who died with and without diagnosed cardiovascular disease. Significant relationships have been found between the chemistry of the drinking water and mortality from cardiovascular disease, as well as certain minerals in the drinking water and cardiovascular disease in autopsy studies.

Investigators in the field of cardiovascular research are aware, however, that mortality rates are notoriously subject to variability and errors because of difficulty in assigning an accurate classification of the cause of death. Autopsy studies, while benefiting from more accurate classification of cause of death, have serious liabilities because of inherent bias from selection of autopsy material.

Another factor in the United States is that people migrate often, which makes it difficult to use mortality data. An individual may have spent a critical period of time (when silent, early stages of disease processes began) in a location distant from the site reporting death.

Given these limitations and problems with data collection, it is a positive feature that so many studies generally agree. It is also possible that clarification of the relationships could be made by another look at some of the data gathered on studies done earlier. If water factors do have an effect on hypertension, stroke, or some other cardiovascular diseases subcategory, simply defining the disease subcategory would limit the number of water factors to consider.

It is not necessary, however, to understand the pathology or even the sequence of water-related disease processes for rational public health measures to be taken, assuming that a clearly defined relationship between a type of water (or water factor) and a disease process is confirmed. It would be most helpful to establish whether the harmful or protective effect

of drinking water is associated with the broad category of cardiovascular disease or with a subtype of this category. For example, if hypertensive disease forms the strongest epidemiologic link, a water factor effect on blood pressure levels and arteriolar structure and function could be sought. If coronary heart disease is involved, the water factor would probably affect the blood clotting mechanism or the progression of atherosclerosis. If no specific subtype of cardiovascular disease can be correlated to the higher mortality resulting from corrosive drinking water, it could be hypothesized that corrosive water is damaging to an already diseased cardiovascular system. In such an association, the water factor would not initiate the cardiovascular disease process, but would influence its progression.

To continue the example, hypertensive disease could be produced by water factors which would produce (or reduce) direct damage to the walls of arteries/arterioles, which would result in elevated blood pressure. The water factor could also cause (or protect against) regulatory system imbalance, changing the blood pressure through the normal renin-angiotensin mechanism or by kidney salt and water retention by the mechanism of hormonal alteration.

If stroke or coronary heart disease had the strongest epidemiologic link to water, a different profile of solutes could be hypothesized. Stroke and coronary heart disease usually involve emboli and atherosclerosis, therefore elements with effects on blood clotting or on the atherosclerotic process would be highly suspect.

Epidemiologic studies can compare the mortality rates of two areas, for example Omaha and Winston-Salem, or Kansas City and Seattle, and say with some degree of assurance that there is a specific rate of cardiovascular mortality in area No. 1, and another specific rate of cardiovascular mortality in area No. 2. Further, the studies can and do point out that the age-adjusted rate of this mortality is significantly high, in the highest decile, or not significantly different from the rest of the United States, or similar general statements. Maps are made of these death rates, and similar maps are made of counties that have corrosive water or mineral-rich water and there is definite overlapping of high mortality rates and corrosive water. It is <u>not</u> possible, however, with the data base available, to calculate the probability of contracting cardiovascular disease for an individual drinking 1.6 to 2 liters/day of area No. 1 water when compared to another individual drinking the same amount of water for the same time from area No. 2. One of the main reasons for the inability to assign an individual risk (without undue and invalidating assumptions) is the lack of any good data (even animal data) on cause-and-effect.

There is also a question of threshold effects. If the only effect of corrosive water on human mortality is one of cardiovascular involvement, then the classic Mantel-Bryan approach for determing a safe threshold dose

could be used, and the limits of corrosiveness could be established. If the health effect is such that corrosive water leaches agents linked to pathologies more serious than cardiovascular disease, it is possible that no threshold would be acceptable. Therefore, the possible solutions are twofold: (1) limits could be expressed in terms of "maximum contaminant levels" for each mineral or other constituent leached from the environment; or (2) corrosivity indices (e.g., LSI, AI, or RI) measuring the calcium carbonate stability of the water, could be used to assure that the non corrosive characteristics of the water are maintained. These decisions cannot be made with the data base presently available, but suggestions in the interest of public health could certainly be made.

5.7 Conclusions

It is apparent from most of the 49 studies in 9 countries, even the poorly controlled studies, that there is a health benefit to man from long-term use of water that is not soft or corrosive. The health benefit most often cited in large studies worldwide relates to cardiovascular disease. The available data do not answer, however, whether the corrosive water is itself chronically toxic (leaching toxicants from the contacted materials) or whether the corrosive water lacks a necessary element for cardiovascular health that is poorly available from dietary sources. It is also considered possible that a protective effect occurs with mineral-rich, hard water that is absent from areas with corrosive water, and is reflected by the greater mortality in the absence of this hypothetical protective solute.

Water corrosiveness certainly affects exposure to trace metals at the consumer's tap. Comprehensive reviews of all studies cannot agree which elements are most likely to be involved in health effects, and, as pointed out above, a consideration of how they are involved should come first. It is, however, the premise of this review that there is no actual need at this point to attempt hypotheses on mechanisms. In fact, while data are insufficient to make mechanistic conclusions, some recommendations based on what is known are in order.

To summarize what is known:

First, mechanisms exist by which cardiovascular damage could occur as a result of trace element intake.

Second, corrosive water contains many metals, leached from the environment, at least four of which have been shown to be involved in facets of cardiovascular disease in experimental animals (and indirectly by human tissue analysis).

Third, epidemiological studies worldwide have found geographical correlation between corrosive water areas and cardiovascular disease.

These repeated variables are consistently correlated in worldwide studies and are not likely to be associated by chance. A cause-effect relationship cannot yet be identified between a specific disease and solutes present in aggressive drinking water. The mechanisms of the health effects of corrosive waters are still in various stages of hypothesis and research, so a traditional risk analysis is not possible. However, it can be concluded that a beneficial effect of hard, mineral-rich drinking water exists.

CHAPTER 6

SUGGESTIONS FOR FUTURE RESEARCH

6.1 Discussion

To recapitulate, the goals of this program were: (a) to determine the distribution of aggressive waters in municipal water supply systems, (b) to estimate the costs of aggressive waters to the utilities distributing them and the costs of chemical stabilization of such waters, and (c) to assess the potential health effects of aggressive waters and the health effects associated with materials which might be released due to contact with aggressive water in a water distribution system. The results discussed in this report have provided some needed first steps toward reaching these goals. However, further effort is both needed and desirable.

Three research programs related to goals (a) and (b) and having considerably different degrees of complexity and purpose will be briefly outlined here. These programs are aimed at overcoming three separate sources of difficulty associated with achieving the above goals. The first level of difficulty involves merely an extension of, and some minor additional analysis based on, the program just completed. Such work would refine the results on the distribution of aggressive waters and their associated costs of stabilization. The number of people exposed to water having varying degrees of aggressiveness (in terms of LSI) when it enters the distribution system has been well established by the present study. However, in the area of estimating losses due to internal corrosion and costs of stabilization there is a substantial benefit to be gained from considerable additional effort.

Two types of problems must be faced in trying to better gauge the extent of losses due to internal corrosion. First, a statistically useful sample must be obtained which will allow those utilities experiencing such losses to be adequately described. The present study yielded considerable nonuniformity in response and its results cannot be extrapolated statistically to missing utilities. Second, there appears to be uncertainty among the utilities themselves as to the extent of their problems. Fully quantifying the situation involves more than just requesting information; it actually involves the development of new data on losses.

The three proposed programs of study are the following:

1. Level 1 Study - Refinement of present work. This extension would involve a characterization of those "missing" utilities not included in the present survey. Such an extension could be done with a relatively modest level of effort. The description of the number of people exposed

to aggressive water would then be essentially complete for the size group studied. (Studies using a sample survey approach should also be carried out on utilities of smaller sizes). Additionally, a further refinement of stabilization costs seems possible. A useful additional step would be to determine treatment costs required to produce a water with a certain degree of oversaturation of $CaCO_3$, rather than just provide an LSI of 0.0 as a final result. Also, a more careful handling of chemical transportation costs is desirable. Finally, treatment costs vary with season and it would be worthwhile to make an effort to account for seasonal variations in treatment requirements and costs.

2. Level 2 Study - Better determination of losses due to internal corrosion. This level of study would require an extensive gathering of new data. The work which has already been done will allow a scientifically designed sample survey to be properly conducted. Some information on the population to be studied is needed before a sample survey can be adequately designed. At the beginning of the present research, information describing the losses experienced by utilities was not available. The fact that such data are now available suggests that they be used to better define the situation. The sample survey would contact only a fraction of all utilities, but it would better describe the nature of the losses to internal corrosion than does the present study. For each utility in the survey there should be interviews at the utility. Information should be collected by firsthand contact with a number of people involved locally. Such an approach would overcome many of the problems of ambiguity, incompleteness and nonresponse, or imcomplete response encountered in the present effort. A level 2 study would greatly improve our knowledge concerning losses due to internal corrosion.

3. Level 3 Study - Detailed studies. A level 2 approach would clarify matters substantially, but it could do no more than assemble and digest information known individually by many utilities, but never combined systematically to provide an overall picture of the problem. It is very likely that many utilities do not fully appreciate the extent of their losses. A level 3 study would closely examine a small group of utilities experiencing, or suspected of experiencing, losses due to internal corrosion. These utilities could be selected from all those studied in a level 1 approach, or better still, chosen randomly from the level 2 sample. The utilities studied in level 3 would be analyzed using experimental data obtained during the study. The experimental data might be obtained from analysis of pipes being replaced, from the chemical analysis of water at various points in a utility's system, or from the use of coupons inserted in the distribution system. Such a study would probably better clarify for the utilitites involved the nature of their problems. The results obtained from such a firsthand study of the problem could be used statistically together with the results from the level 2 study to better estimate the extent of the internal corrosion problem nationally.

In addition, for each utility studied in the level 3 approach, treatment requirements and costs could be carefully determined. This would involve laboratory tests using the actual water in question and would be more valid than a theoretical approach.

REFERENCES

Albanese, A. A., A. H. Edelson, M. L. Woodhull et al., "Effects of a Calcium Supplement on Serum Cholesterol, Calcium, Phosphorus and Bone Density of "Normal, Healthy" Elderly Females," Nutr. Rept. Int., 8:119, 1973.

Allen, K. G. C., and L. M. Klevay, "Cholesterolemia and Cardiovascular Abnormalities in Rats Caused by Copper Deficiency," Atherosclerosis, 29:81-93, 1978.

Allwright SPA, "Mortality and Water Hardness in Three Matched Communities in Los Angeles," Lancet, 2:860, 1974.

Anderson, Y. W., D. Hewitt, L. C. Neri, G. Schreiber, and F. Talbot, "Water Hardness and Magnesium in Heart Muscle," Lancet, 2:1390-1391,1973.

AWWA (American Water Works Association), "AWWA Standard for Asbestos-Cement Distribution Pipe, 4 in. Through 16 in. for Water and Other Liquids," Specificiation C400-77, AWWA, Denver, 1977.

Bierenbaum, M. L., A. I. Fleischman, J. P. Dunn, T. Hayton, D. C. Pattison, and P. B. Watson, "Serum Parameters in Hard and Soft Water Communities," Amer. J. Publ. Health, 63:160, 1973.

Bijlenga, G., E. Dahme, D. K. Detweiler, et al., "Comparative Studies of Atherosclerosis in Swine," Bull. WHO, 36:457- , 1967.

Biorck, G., H. Bostrom, and A. Widstrom, "On the Relationship Between Water Hardness and Death Rate in Cardiovascular Diseases," Acta Med. Scand., 178:239-252, 1965.

Bolton, R. E., and Davis, J. M. G., "The Short Term Effects of Cronic Asbestos Ingestion in Rats," Annals of Occupational Hygiene, 19:121, 1976.

Bonsor, G. M. and Clayson, D. B., "Feeding of Blue Asbestos to Rats," 45th Annual Reports of the British Emisre Cancer Campaign, 1967.

Caddell, J. L., "Studies in Protein-Calorie Malnutrition," New Eng. J. Med., 276:533-535, 1967.

Cairns, J., Jr., and A. Scheier (1968), cited by R. Hartung, loc. cit., 1973.

Camp, T. R., Water and Its Impurities, Reinhold, New York, 1963.

Chase, H. C., "Variation in Heart Disease Mortality Among Counties of New York State," Pub. Health Report, 78:525, 1963.

Chou, W. S., J. E. Savage, and B. L. O'Dell, J. Biol. Chem., 244:5785, 1969.

Chuttani, H. K., P. S. Gupta, et al., "Acute Copper Sulfate Poisoning," Am. J. Med., 39:849, 1965.

Commins, B. T., "Asbestos in Drinking Water: A Review." Technical Report TR100, Water Research Center, Medmenham Laboratories, England. 36 pp. 1979.

Comstock, G. W., "Fatal Arteriosclerotic Heart Disease, Water Hardness at Home, and Socioeconomic Characteristics," Am. J. Epidemiol., 94:1, 1971.

Consolazio, C. F., L. O. Matoush, R. A. Nelson, R. S. Harding, and J. E. Canham, "Excretion of Na, K, Mg, and Fe in Human Sweat and the Relation of Each to Balance and Requirements," J. Nutr., 79:407-514, 1963.

Cook, P. M. and Olson, G. F., "Ingested Mineral Fibers: Elimination in Human Urine," Science, 204:195-198, 1979.

Cornhill, J. F., and A. C. Burton, "Note on Hardness of Drinking Water and City Mortality," cited in Toxic Materials News, 5(28):201, July 12, 1978.

Coulston, F., and E. Mrak (ed.), "Water Quality," Proceedings of an International Symposium, Environmental Protection Agency, Academic Press, New York, p. 114, 1977.

Crawford, M. D., and D. G. Clayton, "Lead in Bones and Drinking Water in Towns with Hard and Soft Water," Brit. Med. J., 2:21-23, 1973.

Crawford, M. D., M. J. Gardner, and J. N. Morris, "Changes in Water Hardness and Local Death-Rates," Lancet, 2:327, 1971.

Crawford, M. D., M. J. Gardner, and J. N. Morris, "Cardiovascular Disease and the Mineral Content of Drinking Water," Brit. Med. Bull., 27:21, 1971.

Crawford, M. D., M. J. Gardner, and J. N. Morris, "Mortality and Hardness of Local Water Supplies," Lancet, 1:827, 1968.

Crawford, T., and M. D. Crawford, "Prevalence and Pathological Changes of Ischaemic Heart Disease in Hard Water and in a Soft Water Area," Lancet, 1:229, 1967.

Cunningham, H. M., Moodie, E., Lawrence G., and Pontefract, R. D., "Chronic Effects of Ingested Asbestos in Rats," Archives of Environmental Contamination and Toxicology, 6:507, 1977.

Dallaire, G., "Are Cities Doing Enough to Remove Cancer-Causing Chemicals from Drinking Water?" Civ. Engr. ASCE, Series on Water Resources No. 1, pp. 88-94, September 1977.

Davies, I. J. T., M. Musa, and T. L. Damandy, "Measurement of Plasma Zinc (II) in Malignant Disease," J. of Clinical Pathol. 21:363-365, 1968.

Dudley, E. F., R. A. Beldin, and B. C. Johnson, "Climate, Water Hardness and Coronary Heart Disease," J. Chron. Dis., 22:25-48, 1969.

Durfor, C. N., and E. Becker, Public Water Supplies and the 100 Largest Cities in the United States 1962, U.S. Geological Survey Water-Supply Paper 1812, Washington, D.C., U.S. Gov't Printing Office, 1964.

Durlach, J., "Le Magnesium en Pathologie Humanie," Rev. Med. Fr., 74:3303-3320, 1967.

Dye, J. F., and J. L. Tuepken, "Chemistry of the Lime-Soda Process," in Water Quality and Treatment: A Handbook of Public Water Supplies, AWWA, 3rd ed., 1971.

Elwood, P. C., M. A. Chadd, M. Burr, and L. M. Hayman, "Blood Clotting and Fibrinolysis in Areas with Different Water Supplies," Brit. J. Prev. Soc. Med. 26:246-248, 1972.

Enterline, P. E., A. E. Rikli, H. I. Sauer, and M. Hyman, "Death Rates for Coronary Heart Disease in Metropolitan and Other Areas," Public Health Report, 75:759, 1960.

Enterline, P. E., and W. H. Steward, "Geographic Patterns in Deaths from Coronary Heart Disease," Public Health Report, 71:849, 1956.

Everson, G. J., L. S. Hurley, and J. F. Geiger, "Manganese Deficiency in the Guinea Pig," J. Nutr., 68:49-56, 1959.

Everson, G. J., and R. E. Shrader, "Abnormal Glucose Tolerance in mn-deficient Guinea Pigs," J. Nutr., 94:89, 1968.

Fears, T. R., "Cancer Mortality and Asbestos Deposits." American Journal of Epidemiology, 104:515-518, 1976.

Federal Register, "Interim Primary Drinking Water Regulations - Control of Organic Chemical Contaminants in Drinking Water," 43(28):5756-5780, 1978.

Freedman, J., (ed.), "Trace Element Geochemistry in Health and Disease," Geological Soc. of America Symposium, Boulder, Colorado, pp. 27-40, 1975.

Genkin, R. I., P. J. Schechter, and R. Hope, "Idiopathic Hypoguesia with Dysguesia, Hyposmia, and Dysosmia--a New Syndrom," J. Amer. Med. Assoc., 217:434-440, 1971.

Gibel, W., K. Lohs, K. G. Wildner, and F. Hoffman, "Tierexperimentelle Untersuchungen uber eine kanzerogene Wirkung von Asbestfilter-material nach Wasseraufnahme." Archive fur Geschwul., 46:437-442, 1976.

Gross, P. Harley, R. A., Swinburne, L. M., Davis, J. M. G., and Greene, W. B., "Ingested Mineral Fibers," Archives of Environmental Health, 29:341-347, 1974.

Gross, S. B., E. A. Pfitzer, et al., "Lead in Human Tissues," Toxicol. Appl. Pharmacol., 32:638-651, 1975.

Hallenbeck, W. H., and C. S. Hesse, "A Review of the Health Effects on Ingested Asbestos." Reviews of Environmental Health, 2(3):157-166, 1967.

Hallenbeck, W. H., and K. Patel-Mandlik, "Fate of Ingested Chrysotile Asbestos Fiber in the Newborn Baboon." PB291686, unpublished report for Health Effects Research Laboratory, U.S. Environmental Protection Agency, Cincinnati, Ohio, 15 pp., 1978.

Harrington, J. M., G. F. Craun, J. W. Meigs, P. J. Landrigan, J. T. Flannery, and R. S. Woodhull, "An Investigation of the Use of Asbestos Cement Pipe for Public Water Supply and the Incidence of Gastrointestinal Cancer in Connecticut, 1935-1973." Am. Journal of Epidemiol., 107(2):96-103, 1978.

Hartung, R., "The Biological Effects of Heavy Metal Pollutants in Water," Proceedings of a Conference on the Role of Metal Ions in Biological Systems, November 20-21, 1972, Argonne, Illinois, Plenum Press, New York, 1973.

Hill, C. H., B. C. Starcher, and C. Kim, "Role of Copper in the Formation of Elastin," Fed. Proc., 26:129, 1967.

Hopkins, L. L., Jr., Am. J. Physiol., 209:731, 1965.

Hopkins, L. L., O. Ransome-Kuti, and A. S. Majaj, "Improvement of Impaired Carbohydrate Metabolism by Chromium III in Malnourished Infants," Amer. J. Clin. Nutr., 21:195, 1968.

Howard, A. N., I. N. Jennings, and G. A. Gresham, "Atherosclerosis in Pigs Obtained from Two Centres Differing in Hardness of Water Supply," Path. Microbiol., 30:676- , 1969.

Hudson, H. E., Jr., and F. W. Gilcreas, "Health and Economic Aspect of Water Hardness and Corrosiveness," J. Am. Water Works Assoc., 68(4):201-204, 1976.

Hurley, L. S., and S. Tao, "Alleviation of Teratogenic Effects of Zinc Deficiency by Simultaneous Lack of Calcium," Am. J. Physio., 222:322-325, 1972.

Jacob, R. A., L. G. Baesler, et al., "Hypercholesterolemia Due to Meat Anemia," Nutr. Rept. Int., 16:73-79, 1977.

Jacobs, R., K. S. Dodgson, and R. J. Richards, "A Preliminary Study of Biochemical Changes in the Rat Small Intestine Following Long-Term Ingestion of Chrysotile Asbestos." British Journal Experimental Pathology, 58:541-548, 1977.

Jones, J. E., R. Manalo, and E. B. Flink, "Magnesium Requirements in Adults," Am. J. Clin. Nutr., 10:632-635, 1964.

Kanarek, M. S., "Asbestos in Drinking Water and Cancer Incidence," doctoral thesis, University of California, Berkeley, September 1978.

Karalekas, P. C., Jr., G. F. Craun, A. F. Hammonds, et al., "Lead and Other Trace Metals in Drinking Water in the Boston Metropolitan Area," J. New Eng. Water Works Assoc., 90:150-172, 1975.

Kehoe, R. A., "The Metabolism of Lead in Man in Health and Disease," J. R. Inst. Publ. Health Hyg., 24:81-97, 129-143, 177-203, 1961.

Kennedy Engineers, Internal Corrosion Study, Phase 1 Report for City of Seattle Water Department, 1976.

Kennedy Engineers, Internal Corrosion Study, Phase 2 and Phase 3 Reports for City of Seattle Water Department, 1978.

Kobayashi, J., "On Geographical Relationship Between the Chemical Nature of River Water and Death Rate from Apoplexy," Ber. Ohara Inst. Landwirt. Biol., 11:12-21, 1957.

Kopp, J. F., and K. C. Kroner, "Trace Metals in Waters of the United States," A five year summary of trace metals in rivers and lakes of the United States, October 1962-September 30, 1967, U.S. Department of the Interior, Federal Water Pollution Control Administration, Division of Pollution Surveillance, Cincinnati, Ohio, 1967.

Kuller, L. H., A. Bolder, and M. S. Saslaw, et al., "Nationwide Cerebrovascular Disease Mortality Study. I. Methods and Analysis of Death Certificates," Am. J. Epidemiol., 90:536, 1969.

Langlier, W. F., "The Analytical Control of Anti-Corrosion Water Treatment," J. Am. Water Works Assoc., 28(10):1500-1521, 1936.

Larson, T. E., "Corrosion-Phenomena-Causes and Cures," in Water Quality and Treatment: A Handbook of Public Water Supplies, AWWA, 3rd ed., 1971.

Larson, T. E., "Corrosion by Domestic Waters," Bulletin 59, Illinois State Water Survey, Urbana, 1975.

Larson, T. E., and A. M. Buswell, "Calcium Carbonate Saturation Index and Alkalinity Interpretations," J. Am. Water Works Assoc., 34(11):1667-1678, 1942.

Lener, J., and B. Bubr, "Cadmium and Hypertension," Lancet, 1:970, 1971.

Levy, B., E. Sigurdson, J. Mandel, E. Laudon, and J. Pearson, "Investigation of Possible Effects of Asbestos in City Water: Surveillance of Gastro-intestinal Cancer Incidences in Duluth, Minnesota." American Journal of Epidemiology, 103:362-368, 1976.

Lijinsky, W., G. M. Singer, and H. W. Taylor, "Carcinogenic N-Nitroso Compounds," in Cancer Epidemiology, Environmental Factors, Vol. 3, Ed. by P. Bucalossi, U. Teronesi, and N. Cascinelii, Elsevier Publisher, New York, pp. 44-47, 1975.

Lindeman, R. D., and J. R. Assenzo, "Correlations Between Water Hardness and Cardiovascular Deaths in Oklahoma Counties," Amer. J. Publ. Health, 54:1071-1077, 1964.

Mandell, A. J., and S. Knapp, "Regulation of Serotonin Biosynthesis in Brain-Role of the High Affinity Uptake of Tryptophan into Serotonergic Neurons," Fed. Proc., 36:2142, 1977.

Masironi, R., "Cardiovascular Mortality in Relation to Radioactivity and Hardness of Local Water Supplies in the USA," Bull. WHO, 43:687-697, 1970.

Massachusetts Department of Public Health, "A High-Risk Community," New Eng. J. Med., 293:1044, November 13, 1975.

Matrone, G., "Manganese" in Geochemistry and the Environment, Vol. II, Nat. Res. Council, N.A.S., Washington, D.C., pp. 29-39, 1977.

McCabe, L. J., and J. C. Vaughn, "Trace Metals Content of Drinking Water from a Large System," National Meeting, American Chemical Society, Minneapolis, Minnesota. 1969.

McKee, J. E., and H. W. Wolf, (ed.), "Water Quality Criteria," 2nd ed., Resources Agency of California State Water Res. Control Board Publication 3-A, Sacramento, December 1963.

Mendelson, J. H., H. Ogata, and N. K. Mello, "Effects of Alcohol Ingestion and Withdrawal on Magnesium States of Alcoholics," Ann. N.Y. Acad. Sci., 162:918-933, 1969.

Merrill, D. T., and R. L. Sanks, "Corrosion Control by Deposition of $CaCO_3$ Films," Parts 1, 2, and 3, J. Am. Water Works Assoc., 69(11):592-600, 1977; 69(12):634-640, 1977; 70(1):12-18, 1978.

Mertz, W., "Biological Role of Chromium," Fed. Proc., 26:186-193, 1967.

Meurman, L. O., Kiviluoto, R., Hakama, M., "Mortality and Morbidity Among the Working Population Anthophyilite Asbestos Workers in Finland," British Journal of Industrial Medicine, 31(2):105-112, April 1974.

Millette, J. R., P. J. Clark, and M. F. Ponsing, "Exposure to Asbestos from Drinking Water in the United States." Health Effects Research Laboratory, U.S. Environmental Protection Agency, Cincinnati, Ohio, 44 pp., 1979.

Millette, J. R., A. F. Hammonds, E. C. Hansen, and M. F. Ponsing, "Agressive Water and Water Utilities from Representative Areas of the United States," submitted to J. Am. Water Works Assoc., 1979.

Morris, J. N., M. D. Crawford, and J. A. Heady, "Hardness of Local Water-Supplies and Mortality from Cardiovascular Disease in the County Boroughs of England and Wales," Lancet, 1:860-862, 1961.

Morton, W. E., "Hypertension and Drinking Water Constituents in Colorado," Amer. J. Publ. Health, 61:1371-1378, 1971.

Mount, D. I., "Chronic Effect of Low pH on Fathead Minnow Survival, Growth and Reproduction," Water Res., 7:987, 1973.

Mulcahy, R., "The Influence of Water Hardness and Rainfall on Cardiovascular and Cerebrovascular Mortality in Ireland," J. Irish Med. Assoc., 59:14-15, 1966.

NAS Committee for Geochemistry, Geochemistry and the Environment, Vol. 2, p. 11, Nat. Acad. Sci., Washington, D.C., 1977.

National Academy of Sciences, National Academy of Engineering, Water Quality Criteria, U.S. Government Printing Office, Washington, D.C., 1972.

National Academy of Sciences-NRC, Division of Medical Science, Medical and Environmental Effects of Environmental Pollutants: Vanadium, Washington, D.C., 1974.

National Technical Advisory Committee to the Secretary of the Interior, Water Quality Criteria, U.S. Government Printing Office, Washington, D.C., 1968.

Neal, J. B., and M. Neal, "Effect of Hard Water and $MgSO_4$ on Rabbit Atherosclerosis," Arch. Pathol., 73:400, 1962.

Neri, L. C., D. Hewitt, and G. B. Schreiber, "Can Epidemiology Elucidate the Water Story?" Amer. J. Epidemiol., 94:101-104, 1971.

Neri, L. C., D. Hewitt, and G. B. Schreiber, "Can Epidemiology Elucidate the Water Story?" Amer. J. Epidemiol, 99:75-88, 1974.

Neri, L. C., D. Hewitt, G. B. Schreiber, et al., "Health Aspects of Hard and Soft Waters," Amer. Water Works Assoc. J., 67(8):403-409, 1975.

Neri, L. C., J. S. Mandel, and D. Hewitt, "Relation Between Mortality and Water Hardness in Canada," Lancet, 1:931-934, 1972.

Newhouse, M. L., Berry, G., Wagner, J. C., et al., "A Study of the Mortality of Female Asbestos Workers," British Journal of Industrial Medicine, 29(2): 134-141, 1972.

O'Dell, B. L., C. E. Burpo, and J. E. Savage, "Evaluation of Zinc Availability in Foodstuffs of Plant and Animal Origin," J. Nutr., 102:653, 1972.

Oliver, P., and L. Murr, "An Electron Microscope Study of Asbestiform Fiber Concentrations in Rio Grande Valley Water Supplies," Journal of American Water Works Association, 69:428-431, 1977.

Olsen, H., "Asbestos in Potable Water Supply," Journal of the American Water Works Association, 66:515-518, 1974.

Perry, H. M., "Minerals in Cardiovascular Disease," J. Amer. Dietetic Assn., 62:631-637, 1973.

Pickering, Q. H., and C. Henderson, Proceedings, 19th Industrial Waste Conference, Purdue University, 1966, Air Water Pollut., 10:453-463, 1965.

Puschner, H., E. Dahme, N. Zollner, et al., "Der Einfluss Weichen und Harten Trinkwassers auf die Ausbildung Arteriosklerotischer Fruhveranderungen und die Plasmalipoide beim Hausschwein," J. Atheroscler, Res., 9:17, 1969.

Radziul, J. V., S. J. Campbell, R, M. Brinkos, and E. J. Shervin, "A Liquid Cement-Calcite Pipe-Coating Process," J. Am. Water Works Assoc., 59(11): 1413-1426, 1967.

Radzuil, J. V., S. L. Campbell, and M. E. Flentje, "New Developments in Deposition of Calcite Linings in Small-Diameter Pipe," J. Am. Water Works Assoc., 57(10):1328-1332, 1965.

Radzuil, J. V., and R. E. Jackson, "Cleaning and Lining of Small Pipe at Philadelphia," J. Am. Water Works Assoc., 57(12):1513-1527, 1967.

Recommended Dietary Allowances, 8th Revised Edition, Committe on Dietary Allowances, Food and Nutrition Board, National Academy of Sciences, Washington, D.C., 1974.

Reinhold, J. G., "Phytate Concentrations of Leavened and Unleavened Iranian Breads," Ecol. Food Nutr., 1:187, 1972.

Reinhold, J. G., "Trace Elements, a Selective Survey," Clin. Chem., 21:476-500, 1975.

Ryznar, J. W., "A New Index for Determining Amount of Calcium Carbonate Scale Formed by a Water," J. Am. Water Works Assoc., 36(4):472-486, 1944.

Sandstead, H. S., "Interactions of Dadmium and Lead With Essential Minerals," in Effects and Dose Response Relationships of Toxic Metals, Ed. by G. F. Nordberg, Elseirer, Amsterdam, pp. 511-526, 1976.

Sauer, H. I., "Epidemiology of Cardiovascular Mortality - Geographic and Ethnic," Amer. J. Pub. Health, 52:94, 1962.

Sauer, H. I., and P. E. Enterline, "Are Geographic Variations in Death Rates for the Cardiovascular Diseases Real?" J. Chron. Dis., 10:513, 1959.

Sauer, H. I., and D. W. Parke, "Counties with Extreme Death Rates and Associated Factors," Am. J. Epidemiol., 99:258, 1974.

Sauer, H. I., D. W. Parke, and M. L. Neill, "Associations Between Drinking Water and Death Rates," in Trace Substances in Environmental Health. IV., ed. by D. D. Hemphill, University of Missouri Press, Columbia, p. 318, 1970.

Sauer, H. I., G. H. Payne, C. R. Council, and J. C. Terrell, "Cardiovascular Disease Mortality Patterns in Georgia and North Carolina." Public Health Report, 81:455, 1966.

Savage, D. C. L., and W. A. McAdam, "Convulsions Due to Hypomagnesemia in An Infant Recovering from Diarrhea," Lancet, 2:234-236, 1967.

Schelling, J. L. S. Muller Hess, and F. Thonney, "Effect of Food on Zinc Absorption," Lancet, 2:969, 1973.

Schou, M. Parmacol. Rev., 9:17- , 1957.

Schreiber, G. B., "Arteriosclerotic Heart Disease Mortality and Water Quality: A Case Against Water Quality Being a Cardiovascular Risk Factor." Unpublished Doctoral Thesis, Johns Hopkins University, School of Hygiene and Public Health, October 1976.

Schroeder, H. A., "Relations Between Mortality from Cardiovascular Disease and Treated Water Supplies," J. Amer. Med. Assoc., 172:98-104, 1960a.

Schroeder, H. A., "The Biological Trace Elements," J. Chron. Dis., 18:217-228, 1965.

Schroeder, H. S., "Cadmium as a Factor in Hypertension," J. Chron. Dis., 18:647, July 1965.

Schroeder, H. S., "Municipal Drinking Water and Cardiovascular Death Rates," J. Amer. Med. Assoc., 195:81-85, 1966.

Schroeder, H. A., and J. J. Balassa, Am. J. Physio., 209:433, 1965.

Schroeder, H. A., J. J. Balassa, and I. H. Tipton, "Abnormal Trace Metals in Man: Chromium," J. Chron. Dis., 15:941, 1962.

Schroeder, H. A., and L. A. Kramer, "Cardiovascular Mortality, Municipal Water, and Corrosion," Arch. Environ. Health, 28:303, 1974.

Schroeder, H. A., A. P. Nason, I. H. Tipton, and J. J. Balassa, "Essential Trace Metals in Man: Copper," J. Chron. Dis., 19:1007-1034, 1966.

Schroeder, H. A., A. P. Nason, I. H. Tipton, and J. J. Balassa, "Essential Trace Metals in Man: Zinc. Relationship to Environmental Cadmium," J. Chron., Dis., 20:179-210, 1967.

Schroeder, H. A., and W. H. Vinton, Jr., Am. J. Physio., 202:515, 1962.

Seelig, M. S., Amer. J. Clin. Nutr. 27:59, 1974.

Selikoff, I., "Epidemiology of Gastrointestinal Cancer," Environmental Health Perspectives, 9:299-305, 1974.

Selikoff, I., E. Hammond, and H. Seidman, "Cancer Risks of Insulation Workers in the United States," Edited by Bogovski, Timbrell, Gilson, Wagner, and Davis. "The Proceedings of the Conference on the Biological Effects of Asbestos." Lyon, France, IARC, World Health Organization, 209-216, 1972.

Severson, R. K., "A Study of the Effects of Asbestos in Drinking Water on Cancer Incidence in the Puget Sound Region." M.S. thesis, unpublished, University of Washington, Seattle, Washington, 110 pp., 1979.

Sharett, A. R., and M. Feinleib, "Water Constituents and Trace Elements in Relation to Cardiovascular Diseases," Prevent. Med., 4:20-36, 1975.

Smith, W. E., "Talc and Nitrates in Relation to Gastric Cancer," American Industrial Hygiene Association Journal, 34:227, 1973.

Smith, W. E. L., Miller, L., Elasser, R. E., and Hubert, D. D., "Tests for Carcinogenicity of Asbestos," Annals of the New York Academy of Sciences, 132:456, 1965.

Stiff, M. J., "Coper/Bicarbonate Equilibria in Solutions of Bicarbonate Ion at Concentrations Similar to Those Found in Natural Water," Water Res., 5:171, 1971.

Storeygard, A. R., and Brown, A. L., "Penetration of the Small Intestinal Mucosa by Asbestos Fibers," Mayo Clinic Proceedings, 52:809-812, 1977.

Tappel, A. L., Amer. J. Clin. Nutr., 27:960-965, 1974.

Voors, A. W., "Does Lithium Depletion Cause Atherosclerotic Heart Disease?" Lancet, 2:1337-1339, 1969.

Voors, A. W., "Minerals in the Municipal Water and Atherosclerotic Heart Death," Amer. J. Epidemio., 93:259, 1971.

Wacker, W. E. C., F. D. Moore, et al., "Normocalcemic Magnesium Deficiency Tetany," J. Amer. Med. Assoc., 180:161-163, 1962.

Wagner, J., G. Berry, T. L. Cooke, R. Hill, F. E. Pooley, and J. Skidmore, "Animal Experiments with Talc." Inhaled Particles and Vapors, IV, Edited by W. C. Walton, Pergamon Press, 1977.

Walker-Smith, J., and J. Blomfield, "Wilson's Disease or Chronic Copper Poisoning?" Arch. Dis. Child., 48:476-479, 1973.

Webster, I., "The Ingestion of Asbestos Fibers," Environmental Health Perspectives," 9:199, 1974.

Westlake, G., "Asbestos Fibers in the Colonic Wall," Environ. Health Perspect., 9:227- , 1974.

Westlake, G., H. Spjut, and M. Smith, "Penetration of Colonic Mucosa by Asbestos Particles," Lab Invest., 14(11):2029-2033, 1965.

Wigle, D. T., "Cancer Mortality in Relation to Asbestos in Municipal Water Supplies," Archives of Environmental Health, 32:185-190, 1977.

Winton, E. F., and L. J. McCabe, "Studies Relating to Water Mineralization and Health," J. Amer. Water Works Assoc., 62:26, 1970.

APPENDIX I

CHEMICAL ADDITIONS

Two approaches to stabilization of waters were considered. The first assumed a water to be "stabilized" when its Langlier Saturation Index (LSI) had been increased to zero by the addition of chemicals. A maximum pH of 9.5 was allowed. The second approach required an LSI of zero or above also, but had the further requirements that the final alkalinity of the water be 40 mg/liter as $CaCO_3$ or greater and that the final calcium concentration be 16 mg/liter or greater (as Ca). The final pH was also restricted to being either 7.3 or 8.6. The second approach produces a much more stable water. (It is also more expensive.)

For both approaches, pH, alkalinity, and calcium concentration were adjusted by addition of lime and carbon dioxide. Lime was used to increase alkalinity, calcium concentration, and pH. CO_2 was used to maintain pH at the desired level if that was reached because of the addition of lime. Substitutes for CO_2 exist, but CO_2 has theoretical advantages. However, CO_2 has had limited field use.

The following describes the algorithms used to determine the quantities of chemical required for the two approaches. All quantities of chemicals determined are theoretical.

Approach 1: No minimum alkalinity or calcium concentration required; pH less than or equal to 9.5. Specifically, the following operations were used:

Step 1 - Add lime until LSI = 0 or until pH = 9.5;

Step 2 - If LSI = 0 with pH $\leq$ 9.5, operation ends; and

Step 3 - If LSI < 0 at pH = 9.5, add CO_2 and lime together in such combination as to maintain pH = 9.5, but to increase the calcium concentrations and alkalinity of the water until LSI = 0.

The analysis assumes that buffering is provided only by the carbonate system. Alkalinity is then given by:

$$Alk = [HCO_3^-] + 2[CO_3^=] + [OH^-] - [H^+]$$

where the concentrations are in moles per liter.

We may define C_T as:

$$C_T = [H_2CO_3] + [HCO_3^-] + [CO_3^=]$$

where C_T is the total carbonate carbon.

Then,

$$Alk = C_T\ (\alpha_1 + 2\alpha_2) + [OH^-] - [H^+]$$

where α_1 and α_2 are ionization fractions for carbonic acid and are given by:

$$\alpha_1 = \left(\frac{[H^+]}{K_1} + 1 + \frac{K_2}{[H^+]}\right)^{-1} = \frac{[HCO_3^-]}{C_T}$$

$$\alpha_2 = \left(\frac{[H^+]^2}{K_1K_2} + \frac{[H^+]}{K_2} + 1\right)^{-1} = \frac{[CO_3^=]}{C_T}$$

K_1 and K_2 are ionization constants for carbonic acid.

Let $\alpha = \alpha_1 + 2\alpha_2$

then,

$$Alk = C_T\alpha + [OH^-] - [H^+] \qquad (1)$$

and

$$C_T = \frac{Alk - [OH^-] + [H^+]}{\alpha} \qquad (2)$$

Initially the water has a pH = pH_o, and alkalinity of Alk_o and a calcium concentration of Ca_o. Using these values and the temperature of the water, C_T for the water can be found using Eq. (2).

C_T does not change if a base such as lime, $Ca(OH)_2$, is added. Therefore, Step 1 in the algorithm is carried out as follows. Increment pH by 0.1 unit (i.e., decrease $[H^+]$ in Eq. (1). Determine alkalinity (Alk') at this new pH = pH' using Eq. (1) (C_T is constant). Then using the fact that the addition of one equivalent per liter of strong base results in the increase of one equivalent per liter of alkalinity,

$$C_B = Alk' - Alk_o$$

$$\text{Lime added} = 37{,}040\ C_B\ (\text{mg/liter})$$

The equivalent weight of lime is 37.04 and this is multiplied by 1,000 to give concentrations in the above expression in milligrams per liter.

Similarly, the calcium added is:

$$\text{Calcium added} = \frac{40.08}{74.09} \text{ (lime added)} \quad \text{(mg/liter)}$$

The gram formula weight of Ca is 40.08; the gram formula weight of $Ca(OH)_2$ is 74.09. Total dissolved solids (TDS) concentration increases by the amount of the increase in calcium concentration. Thus, we have found the quantity of lime (milligrams per liter) required to increase pH by 0.1 unit and have found the increments in calcium, alkalinity, and TDS accompanying this pH change. At $pH' = pH_o + 0.1$, the value of LSI is determined. If $LSI \geq 0$, the water is "stable." We then have the lime addition required to accomplish this (Step 2 is finished).

If $LSI < 0$ after the lime addition, the above operation (increment pH, find lime addition required, find new alkalinity, etc.) is repeated until $pH = 9.5$ is reached or until $LSI \geq 0$, whichever occurs first.

If $LSI < 0$ at $pH = 9.5$, we proceed to Step 3 in the algorithm. Here, both lime and CO_2 are added.

The quantity of lime and CO_2 needed to reach $LSI = 0$ are determined as follows. A constant $pH = 9.5$ is held; lime is added until the product of the calcium concentration and the alkalinity is large enough to give an $LSI = 0$ at $pH = 9.5$. The quantity of CO_2 required to maintain a constant $pH = 9.5$ is determined.

Using the expression given in Appendix IV for the LSI, the product $[Ca] \times [Alk]$ required to give $LSI = 0$ at $pH = 9.5$ can be found by the simple solution of a quadratic equation. Solution of the equation gives the final values of $[Ca] = [Ca'']$ and $[Alk] = [Alk'']$; from these values the lime requirement is determined.

The addition of CO_2 increases C_T. Addition of a molar increment of CO_2 increases C_T by the same amount. Since $[Alk'']$ is known,

$$C_T'' = \left. \frac{Alk'' - [OH^-] + [H^+]}{\alpha} \right| \; pH = 9.5$$

The change in C_T is given by:

$$\Delta C_T = C_T'' - C_{T_o}$$

The CO_2 required to maintain pH constant is then given by:

$$[CO_2] = 44011\Delta C_T \quad \text{(mg/liter)}$$

44.011 is the molecular weight of CO_2.

We have, therefore, completed Step 3 in the algorithm and have determined the lime and CO_2 additions required to give an LSI = 0 at pH = 9.5.

In finding α in the above calculations, values for K_1 and K_2 taken from Larson and Buswell (1942) were used. The data given there were fitted by the following expression:

$$K_1 = (0.0626\ T + 2.75) \times 10^{-7}$$

where T is temperature (^oC) and $0 \leq T \leq 30$;

$$K_2 = (0.0923\ T + 2.36) \times 10^{-11}$$

where $0 \leq T \leq 40$.

Approach 2: Minimum values of calcium concentration and alkalinity required. Restrictions placed on pH. Certain ranges of pH are less desirable than others since buffering capacity is lower. A high pH results in a $CaCO_3$ scale of inferior quality and if pH is sufficiently high, $Mg(OH)_2$ scaling in hot water heaters may occur. A minimum value for alkalinity of 40 mg/liter as $CaCO_3$ and a minimum calcium concentration of 16 mg/liter are thought desirable for a high quality, stable water. Producing such a water is more expensive than is the use of Approach 1. The algorithm used here allows a high quality water to be produced and determines the necessary chemical additions.

Step 1 - If pH < 7.3, add lime until pH = 7.3,
if 7.3 < pH < 8.6, add lime until pH = 8.6,
if pH > 8.6, add CO_2 until pH = 8.6;

Step 2 - Add lime until alkalinity = 40 mg/liter as $CaCO_3$,
maintain pH constant with CO_2 additions;

Step 3 - Add lime until calcium concentration = 16 mg/liter,
maintain pH constant with CO_2;

Step 4 - If LSI < 0 after these operations, add lime and CO_2 until LSI = 0 (at constant pH).

The calculations are very similar to those for Approach 1 and will not be described.

APPENDIX II

COSTS OF CHEMICAL ADDITIONS

Two chemicals were used in the analysis: lime and carbon dioxide. This appendix describes the basis for the cost calculations for these two chemicals.

A. Lime

Lime is available in two forms, hydrated and quicklime. Hydrated lime does not require slaking prior to use, but is more expensive to buy and more bulky. Usually hydrated lime is preferred in small operations, and quicklime is used in larger ones. However, the cost difference is small. For the purposes of this analysis, quicklime will be used for all calculations.

At the time this report was prepared, quicklime was available at $32.50/ton (FOB plant).* This value was used in the analysis. The material was assumed to have an availability of 90% as CaO.

Lime delivery costs may be quite significant, but were not included specifically in the analysis since the haul distances for the various utilities involved were not known. The influence of delivery costs was considered in the sensitivity analysis.

The cost of a lime handling system, including storage silo, dry feeders, slaker, slurry tank, pump and mixer is estimated at $150,000. This system will deliver lime at rates up to 500 lb/hr. For utilities requiring lime at a higher rate, multiples of this system were used. It is quite possible that a more economical system could be designed for particular utilities. However, since no specific information other than water quality-related characteristics were available, a general, conservative approach to costing was taken.

The cost for the lime system assumes no new building construction (other than the silo).

The lime system requires roughly 1 man-hr/day to operate. The lifetime of the system is roughly 30 years. The maintenance requirement is low and has been assumed to be 1% of the capital cost per year.

In addition to the lime feed system, a control system to maintain pH is needed. The capital cost is estimated at $10,000.00.

The energy costs to operate the system were neglected; however, it is anticipated that they will be quite small compared to other expenses.

* Chemical Marketing Reporter, January 29, 1979. p. 41.

B. Carbon Dioxide

Carbon dioxide can be purchased in bulk or generated on-site by combustion. Bulk purchase is simpler and results in a higher quality material (nearly 100% CO_2). Because of the availability of bulk CO_2 in a wide range of volumes and because of the simplicity of the cost estimate, bulk CO_2 is assumed in the analysis.

Chemical costs are given in Table II-1. These costs were obtained from a chemical supplier. Transportation costs are not included.

The system to supply the carbon dioxide to the water consists of a storage facility, a vaporizer, and a line mixer for feeding the gas into the water. Table II-2 lists cost estimates for such a system versus size.

It is estimated that the system for feeding CO_2 requires about 20 hr of labor per year.

The CO_2 system is very simple and should require very little maintenance. An annual cost of 1% of the capital cost was assumed. Lifetime for the system should exceed 20 years.

Energy costs were neglected and it was assumed that the same pH control system used with the lime feed system could be used with this system as well.

C. General

In all calculations a labor cost of $10.00/hr plus 50% for overhead and supervision was assumed. The cost estimates assume that no new building construction is required and that needed facilities could be accommodated on the present site of the water treatment plant. The labor requirements are minimal and, generally speaking, no new employees would be required to operate the lime and CO_2 systems. However, since some time is required it is appropriate to charge the new systems with the appropriate time costs.

Annual capital costs were determined based on the assumption that capital expenditures would be finance using Municipal Water Revenue Bonds at 6% interest for 20 years.

TABLE II-1

CARBON DIOXIDE COSTS

Rate Used (ton/year)	Cost ($/ton)
0-50	180
50-100	156
100-300	104
300-500	100
500-1,000	75
1,000-2,000	60
Above 2,000	48

TABLE II-2

CARBON DIOXIDE HANDLING SYSTEM

Size (ton/year)	Capital Cost ($)
0-100	14,000
100-300	17,500
300-500	21,500
500-1,000	29,000
1,000-2,000	41,500
Above 2,000	Add additional units of preceding sizes as needed

APPENDIX III

LANGLIER SATURATION INDEX

The Langlier Saturation Index (LSI) was discussed in Chapter I. This appendix provides some additional details concerning the calculation of LSI.

As noted in Chapter 1:

$$LSI = pH_{Measured} - pH_{Saturation}$$

and $$pH_{Saturation} = \log \frac{K_s}{K_2} - \log[Ca^{++}] - \log[Alk] + 9.30 + \frac{2.5\sqrt{\mu}}{1 + 5.3\sqrt{\mu} + 5.5}$$

where: K_s = Solubility constant for $CaCO_3$,

K_2 = Second ionization constant for H_2CO_3,

$[Ca^{++}]$ = Calcium concentration (mg/liter),

$[Alk]$ = Alkalinity (mg/liter as $CaCO_3$), and

μ = ionic strength.

K_s and K_2 were estimated using values provided by Larson and Buswell (1942). Their data were approximated by the following equations:

$$K_s = [10^{(0.978 - 0.0125T)}] \times 10^{-9}$$

and $$K_2 = (0.0923T + 2.36) \times 10^{-11}$$

T is temperature and $0^{o}C \leq T \leq 40^{o}C$.

Ionic strength was approximated by 2.5×10^{-5} times the total dissolved solids (TDS) concentration in mg/liter. Such an approximation is reasonable for TDS < 500 mg/liter.

LSI was calculated whenever possible using temperature values provided by the utilities. If values for temperature were not provided by a utility, a temperature of $10^{o}C$ was used in determining chemical additions required for stabilization of the water. Average values of other parameters (as provided by the utility) were used with both minimum and maximum temperatures. No temperature variation was considered in the other parameters. LSI was determined at minimum temperature, which gives (with average values) a minimum value of LSI and maximum (and, hence, conservative) amount of chemical required for stabilization.

APPENDIX IV

BIBLIOGRAPHY

A/C Pipe Producers Association, "A/C Pipe and Health," Arlington, Virginia, 1978.

Alpert, J., and D. Harrington, "Economic Evaluation of the Promulgated Interim Primary Drinking Water Regulations," U.S. Environmental Protection Agency, EPA-570/9-75-003, October 1975.

Anderson, C. H., and J. M. Long, "Preliminary Interim Procedure for Fibrous Asbestos," U.S. Environmental Protection Agency, Environmental Research Laboratory, Athens, Georgia, July 31, 1976.

Angino, E., et al., "Drinking Water Quality and Chronic Disease," Environmental Science and Technology, 2(7):660-665, 1977.

AWWA Standards Committee, "Asbestos-Cement Pressure Pipe - 4 in. Through 24 in. for Water and Other Liquids," AWWA C400-75, January 1975.

Baylis, J. R., "Prevention of Corrosion and 'Red Water'," JAWWA, 15:598, 1926.

Baylis, J. R., "Cast-Iron Pipe Coatings and Corrosion," JAWWA, 45:807-831, August 1953.

Bennett, L. H., Kruger, J., et al., "Economic Effects of Metallic Corrosion in the United States," U.S. Department of Commerce, National Bureau of Standards Report No. 511-1, May 1978.

Caldwell, D. H., and W. B. Lawrence, "Water Softening and Conditioning Problems," Industrial and Engineering Chemistry, 45(3):535-548, 1953.

Caplan, F., "Is Your Water Scaling or Corrosive?" Chemical Engineering, p. 129, September 1975.

Carlberg, B. L., and R. R. Matthews, "Continuous Membranes to Supplement and Improve Cement Linings for Pipe," Materials Protection and Performance, 11(8):33-36, 1972.

Chambers, A., D. Hilt, and B. Steven, "An Updated Hartford Metropolitan District Water Rate Survey," JAWWA, 252-255, 1978.

Clark, R. M., "The Cost of Water Supply and Water Utility Management," Water Supply Research Division, Municipal Environmental Research Laboratory, EPA-600/5-77-015a, November 1977.

Clark, R. M., and J. I. Gillean, "The Cost of Water Supply Utility Management," in Environmental Modeling and Simulation, Proceedings of a Conference, U.S. Environmental Protection Agency, EPA-600/9-76-016, Cincinnati, Ohio, pp. 808-813, April 1976.

Clark, R. M., and H. C. Goddard, "Cost and Quality of Water Supply," JAWWA, 69(1), 1977.

Clark, R. M., et al., "The Cost of Removing Chloroform and Other Trihalomethanes from Drinking Water Supplies," U.S. Environmental Protection Agency, EPA-600/1-77-608, March 1977.

Clark, R. M., R. Stevie, and G. Trygy, "The Cost of Municipal Water Supply: A Case Study," U.S. Environmental Protection Agency, EPA-600/2-76-179, Cincinnati, Ohio, July 1976.

Cohen, A., and W. S. Lyman, "Service Experience with Copper Plumbing Tube," Materials Protection and Performance, 2(2): 48-52, 1972.

Craun, G. F., and L. J. McCabe, "Problems Associated With Metals in Drinking Water," JAWWA, 593-599, 1975.

Culver, R. H., "Soft Water: A Distribution Problem," Water and Sewage Works, pp. 52-55, February 1975.

Cunningham, H. M., and R. Pontefract, "Asbestos Fibers in Beverages and Drinking Water," Nature, 232:322, July 1971.

Curry, M. D., "Is Your Water Stable and What Difference Does It Make?," JAWWA, 506-512, September 1978.

Dangel, A., "Study of Corrosion Products in the Seattle Water Department Tolt Distribution System," NTIS, U.S. Department of Commerce, May 1975.

Dart, F. S., "The Hazard of Iron," Water and Pollution Control, pp. 19-23; 38, 1974.

Dolson, F. E., "Maintaining Water Quality in Distribution Systems," JAWWA, January 1962.

Eick, I. H., "Corrosion in Asbestos Cement and Concrete," International Water Supply Association, Specialist Sessions and Proceedings of the Congress, Corrosion Day Report No. 3, Eighth Congress, 1969, pp. T30-T43.

Geld, I., and C. McCaul, "Corrosion and Coatings Test Program of the NYC Board of Water Supply," Materials Protection and Performance, February 1972.

Geld, I., and C. McCaul, "Corrosion in Potable Water," JAWWA, pp. 549-552, October 1975.

Hatch, G. C., "Polyphosphate Inhibitors in Potable Water," Materials Protection, pp. 31-35, November 1969.

Hatch, G. B., and O. Rice, "Corrosion Control With Threshold Treatment - Factors in Formation of Protective Films Upon Steel by Waters Treated With Glassy Phosphates," Industrial and Engineering Chemistry, August 1945.

Hang, I., et al., "Final Report and Recommendations of the Seattle Internal Corrosion Study Advisory Committee," Seattle Water Department, Seattle, Washington, May 1978.

Hausler, R. H., "Economics of Corrosion Control," Materials Performance, pp. 9-12, November 1977.

Hoffman, D. A., and F. O. Waters, "Using Cast Iron Pipe in Highly Corrosive Environments," Materials Protection, pp. 21-22, May 1966.

Holler, A. C., "Corrosion of Water Pipes," JAWWA, August 1974.

Hoxie, E. C., "Corrosion of Well Points and Piping in Domestic Water Near AEC Plant," Materials Protection, pp. 65-67, October 1963.

Kennedy Engineers, "Internal Corrosion Study," Summary Report for the City of Seattle, Washington, Tacoma, Washington, February 17, 1978.

Krasauskas, J. W., "Delivery of a Public Water Supply: Standards, Safeguards, and Differences," Medical Instrumentation, 8(3):197-200, 1974.

Kuschner, M. "A Study of the Problem of Asbestos in Water," JAWWA, Part 2, p. 22, September 1974.

Lamb, J. C. III, and R. Eliassen, "Corrosion Control with Metaphosphate Glass," JNEWWA, 69:31, 1955.

Lane, R. W., C. H. Neff, and S. W. Schilsky, "Silicate Treatment to Inhibit Corrosion of Hot, Potable Water Systems, Phase 1," Air Force Weapons Laboratory, Technical Report No. AFWL-TR-71-58, August 1971.

Langelier, W. F., "Chemical Equilibria in Water Treatment JAWWA, 38(2):169-178, 1946.

Larson, T. E., "The Ideal Lime-Softened Water," JAWWA, 43: 649-664, 1951.

Larson, T. E., "Report on Loss in Carrying Capacity of Water Mains," JAWWA, 47:1061, 1955.

Larson, T. E., "Chemical Control of Corrosion," JAWWA, pp. 354-362, 1966.

Larson, T. E., "Corrosion by Domestic Waters," W&SE, Ref. No. 1976, pp. R-176 to R-183.

Larson, T. E., and R. M. King, "Corrosion by Water at Low Flow Velocity," JAWWA, 46(1), January 1954.

Larson, T. E., R. W. Lane, and C. H. Neff, "Stabilization of Magnesium Hydroxide in the Solids-Contact Process," JAWWA, pp. 1551-1558, December 1959.

Larson, T. E., and F. F. McGurk, "Complexes Affecting the Solubility of Calcium Carbonate in Water," Final Report, University of Illinois Water Resources Center, pp. 1-49, June 30, 1973.

Larson, T. E., and R. V. Skold, "Corrosion and Tuberculation of Cast Iron," JAWWA, 49:1294, 1957.

Larson, T. E., and R. V. Skold, "Laboratory Studies Relating Mineral Quality of Water to Corrosion of Steel and Cast Iron," Corrosion, 14:285, 1957.

Larson, T. E., and R. V. Skold, "Current Research on Corrosion and Tuberculation of Cast Iron," JAWWA, 49:1429, 1958.

Larson, T. E. F. W. Sollo, and F. F. McGurk, "Complexes Affecting the Solubility of Calcium Carbonate in Water - Phase II," Final Report, University of Illinois Water Resource Center, Urbana, Illinois, pp. 1-57, February 1976.

Laubusch, E. J., "Chlorination and Other Disinfection Processes," Water Quality and Treatment, AWWA, 3rd ed., 1971.

Levin, A., "The Rural Water Survey," JAWWA, pp. 446-452, August 1978.

Lowthian, K. M., "Draft Environmental Impact Statement for the Proposed Seattle Corrosion Control Plan," The Seattle Water Department, August 1, 1978.

Lyon, D. B., and J. M. A. Lenihan, "Corrosion in Solder Jointed Copper Tubes Resulting in Lead Contamination of Drinking Water," Br. Corros. J., 12(1):41-45, 1977.

McCauley, R. F., "Protective Coatings for Water Distribution Systems," JAWWA, October 1957.

McCauley, R. F., "Controlled Deposition of Protective Calcite Coatings in Water Mains," JAWWA, November 1960.

McFarren, E. F., et al., "Water Quality Deterioration in the Distribution System," Paper presented at Water Quality Technology Conference, Kansas City, Missouri, December 5-6, 1977, Water Supply Research Division, U.S. Environmental Protection Agency, Cincinnati, Ohio.

Mullen, E. D., and J. A. Ritter, "Potable-Water Corrosion Control," JAWWA, August 1974.

Myers, J. R., and M. F. Obrecht, "Potable Water Systems - Recognition of Cause Vital in Minimizing Corrosion," Materials Protection and Performance, 11(4):41-46, 1972.

Myers, J. R., and M. F. Obrecht, "Performance and Selection of Materials for Potable Hot Water Service," Materials Protection and Performance, 12(4):1973.

NACE, "Second Corrosive Study of Pipe Exposed to Domestic Waters," NACE Publication No. 7B170, Materials Protection, pp. 34-37, June 1970.

Overman, J. P., "System for Numerically Rating Water Supply Systems," Hittman Associates, Inc., Columbia, Maryland, NTIS-253-321, February 1973.

Part, F. J., "Interior Corrosion of Pipelines," Water and Pollution Control, pp. 23-26; 35, December 1975.

Payer, J. H. D. G. Dippold, et al., "Economic Effects of Metallic Corrosion in the United States," Appendix B, Battelle Columbus Laboratories, Columbus, Ohio, pp. 1-167, May 1978.

Payer, J. H., D. G., Dippold, et al., "Economic Effects of Metallic Corrosion in the United States," Appendix C, Battelle Columbus Laboratories, Colubus, Ohio, pp. 1-746.

Pearson, I. E., and P. R. Singer, "Water Quality Considerations in Water Distribution from Two Sources," JAWWA, pp. 600-605, October 1974.

Pluntze, J. C., "How Will Small Utilities Comply with Safe Drinking Water Act," Water and Sewage Works, pp. 50-53, January 1977.

Proudfit, D. P., G. C. Collins, and H. K. Murray, "Balancing Needs, Responsibility, and Costs in the Distribution System," JAWWA, pp. 629-638, June 1970.

Pryor, M. J., and M. Cohen, "The Mechanism of the Inhibition of the Corrosion of Iron by Solutions of Sodium Orthophosphate," Journal of the Electrochemical Society, July 1951.

Quint, S. M., "Transite Pipe Test Line - Determination of Asbestos Fiber in Water," John-Manville Research and Engineering Center, Report No. 425-T-1360, September 29, 1971.

Randolph, R. C., and D. A. Lincoln, "Corrosive Effects of Potable Water," Materials Protection and Performance, 12(4): 25-27, 1973.

Reedy, D. R., "Corrosive Effects of Southern California Potable Waters," Materials Protection and Performance, 12(4): 43-48, 1973.

Reedy, D. R., "Corrosion in the Water Works Industry," Materials Protection, pp. 55-59, September 1976.

Regnier, J. E., "Monitoring Potable Waters," Environmental Science and Technology, 11(1):40-43, January 1977.

Reinhart, F. M., and J. F. Jenkins, "Design for Corrosion Control of Potable Water Distribution Systems," NTIS, AD/A-006 806, Naval Civil Engineering Laboratory, February 1975.

Ryder, R. A., and P. H. Solbert, "Corrosion Conditions and Correction of Seattle's Mountain Pure Water," JAWWA, Annual Conference, Pacific Northwest Section, Olympia, Washington, pp. 1-6, May 19, 1978.

Sargent, H. E., "Asbestos in Drinking Water," Presented NEWWA Meeting, Northfield, Vermont, May 17, 1973.

Skold, R. V., and T. E. Larson, "Measurement of the Instantaneous Corrosion Rate by Means of Polarization Data," Corrosion, 13:139, 1957.

Stacha, J. H., "Criteria for Pipeline Replacement," JAWWA, pp. 256-258, May 1978.

Steinour, H. H., "Estimation of Aggressive CO_2 and Comparison with Langelier Saturation Index," Research and Development Laboratories, Portland Cement Association, Skokie, Illinois, October 1975.

Streicher, L., "Effects of Water Quality on Various Metals," JAWWA, 50(3), March 1956.

Stumm, W., "Calcium Carbonate Deposition at Iron Surfaces," JAWWA, March 1956.

Stumm, W., "Corrosion Studies," Public Works, December 1957.

Stumm, W., "Estimating Corrosion Rates in Water," Industrial and Engineering Chemistry, 51(12):1487-1490, 1959.

Stumm, W., "Investigation on the Corrosion Behavior of Waters," ASCE, Journal of the Sanitary Engineering Division, pp. 27-45, November 1960.

Temple, B., and Sloane, Inc., "Economic Impact Analysis of a Trihalomethane Regulation for Drinking Water, MCL of THM at 0.10 Milligrams/Liter for Large Water Systems," EPA, PB-271 813, U.S. Department of Commerce, NTIS, August 1977.

Trivers, R. E., et al., "Water Distribution System Corrosion Control," JAWWA, August 1974.

U.S. Environmental Protection Agency, Manual on the Use of the Public Health Service Drinking Water Standard, 1971.

U.S. Environmental Protection Agency, Manual of Individual Water Supply Systems, EPA 430/9-74-007, 1972.

Wagner, J. M., "Corrosion Control Law and Its Effect on Water-Distribution Systems," JAWWA, August 1974.

Waters, F. O., "Corrosion in Municipal Water Systems," Materials Protection and Performance, 10(4):23-25, 1971.

Whitlock, E. W., "Concrete Pressure Pipe in Today's Water Industry," JAWWA, October 1960.

APPENDIX V

BIBLIOGRAPHY OF SECONDARY SOURCES OF DATA

Alabama State Department of Public Health, "Chemical Analyses of Water from Alabama Public Water Supplies," Bureau of Environmental Health, Montgomery, 1966.

AWWA, "Operating Data for Water Utilities 1970 and 1965," AWWA No. 20112, New York, no date.

AWWA, "Operating Data for Water Utilities 1976," Preliminary, Prepublication Copy.

Arkansas State Department of Health, "Arkansas Municipal Water Supplies Chemical Data," Bureau of Environmental Engineering, no date.

Colorado Department of Health, "Colorado Drinking Water Supplies, February 1971, Chemical Quality," Division of Engineering and Sanitation, Denver.

Connecticut State Department of Health, "Analyses of Connecticut Public Water Supplies, Five-Year Average 1971-1975," Report No. EHS 17A(7-76)1M, Hartford, 8th ed., 1976.

Dial, Don C., "Public Water Supplies in Louisiana," Basic Records Report No. 3, U.S. Geological Survey in Cooperation with Louisiana Department of Public Works, Baton Rouge, 1970.

Durfor, C. N., and E. Becker, "Public Water Supplies of the 100 Largest Cities in the United States, 1962," Geological Survey Water Supply Paper 1812, USGPO, 1964.

Florida State Department of Health, "Inventory of Public Water Supplies in Florida, 1956," Bureau of Sanitary Engineering, Jacksonville.

Florida State Department of Health, "Some Physical and Chemical Characteristics of Selected Florida Waters," Bureau of Sanitary Engineering, Jacksonville, June 1964 and June 1968.

Florida State Department of Health and Rehabilitative Services, "Review of Selected Properties of Florida Water - 1969," Division of Health, Bureau of Sanitary Engineering, Jacksonville, 1969.

Illinois, State of, Environmental Protection Agency, "Public Water Supplies Data Book," July 1, 1973.

Indiana State Board of Health, "Data on Indiana Public Water Supplies," Bulletin No. SE1G, Division of Sanitary Engineering and Bureau of Laboratories, Indianapolis, January 1968.

Iowa Department of Environmental Quality (L. Apple), personal communication, 1979.

Kansas Department of Health and Environment (T. S. Watkins), personal communication, Topeka, 1978.

Kentucky Department for Nature Resources and Environmental Protection (D. J. Linden), personal communication, Frankfort, 1979.

Lohr, E. W., and S. K. Love, "The Industrial Utility of Public Water Supplies in the United States, 1952, Part I. States East of the Mississippi River," Geological Survey Water Supply Paper 1299, USGPO, 1954.

Lohr, E. W., and S. K. Love, "The Industrial Utility of Public Water Supplies in the United States, 1952, Part 2. States West of the Mississippi River," Geological Survey Water Supply Paper 1300, USGPO, 1954.

Massachusetts Department of Environmental Quality Engineering, "Public Water Supplies in Massachusetts, 1976," Division of Water Supply, 1976.

Michigan State Department of Health, personal communication, 1979.

Minnesota State Department of Health (S. Greenwood), personal communication, 1979.

Missouri Department of Natural Resources, "Census of Missouri Public Water Supplies," 1977, Division of Environmental Quality.

Nebraska State Department of Health, "Chemical Analyses of Nebraska Municipal Water Supplies," Division of Environmental Engineering, Lincoln, January 1973.

New Jersey Department of Environmental Protection (J. Hroncich), personal communication, Trenton, 1978.

Oklahoma State Department of Health, "Chemical Analyses of Public Water Supplies in Oklahoma 1968," O. D. H. Engineering Bulletin No. 0597-B, 1968.

South Dakota Department of Environmental Protection, "South Dakota Public Water Supply Data," January 1979.

Texas Department of Health, "Chemical Analysis of Public Water Supplies," Division of Water Hygiene, 1977.

U.S. Geological Survey, "Quality of Public Water Supplies of New York," November 1970 - April 1972," open file report, in cooperation with New York State Department of Health, 1974.

U.S. Geological Survey, "Quality of Public Water Supplies of New York," May 1972 - May 1973," open file report, in cooperation with New York State Department of Health, 1975.

U.S. Geological Survey, "Chemical Quality of Water in Community Systems in New York May 1973 - May 1974," open file report, in cooperation with New York State Department of Health, 1976.

U.S. Geological Survey, "Chemical Quality of Water in Community Systems in New York, May 1974 - May 1975," open file report, in cooperation with New York State Department of Health, 1977.

Wisconsin Department of Natural Resources (M. H. Bridwell), personal communication, Madison, 1979.