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HEALTH AND CORROSION
IMPACT OF SOFT WATER

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1. EXECUTIVE SUMMARY

1.1 INTRODUCTION

Certain chemical constituents released into public drinking water systems by corrosive action can pose potential health hazards. Further, extensive epidemiological research has strongly suggested that consumption of soft and sometimes aggressive drinking water may be related to increased incidence of cardiovascular disease. It has also been recognized that aggressive water in distribution systems rapidly increases corrosion rates and thereby increases the rate of pipe replacement and the costs associated with it. The purpose of this report is:

- to delineate the health issues involved in consumption of soft and/or corrosive water
- to elucidate mechanisms by which soft water is implicated in cardiovascular disease
- to quantify health and corrosion costs of aggressive water
- to examine corrosion treatment options in terms of cost-effectiveness and health benefits.

1.2 SUMMARY OF FINDINGS

Health Impacts

- Medical studies have shown a high statistical correlation between soft water and cardiovascular heart disease (CVD).
- All known risk factors account for only 50 percent of the incidence of cardiovascular disease, excluding the risk from the consumption of drinking water. Drinking water may account for a significant fraction of the remaining 50 percent.
- As shown in Table 1-1, the cause and effect mechanisms of this relationship can be hypothesized into three classes.

TABLE 1.1

CLASSIFICATION OF RELATIONSHIPS OF DRINKING WATER TO CARDIOVASCULAR DISEASE

Class I	One or more of the major components of hard water are protective. These beneficial elements are lacking in soft water. • Magnesium • Calcium
Class 2	One or more of the minor components ("trace" elements) that tend to be present in hard water, but absent or deficient in soft water, are protective. • Lithium • Chromium • Vanadium • Selenium • Manganese • Strontium
Class 3	One or more components in soft water are harmful -- this includes metal ions that are leached from the distribution system. • Cadmium • Copper • Lead • Beryllium

- As shown in Table 1-2, water treatment techniques may reduce the incidence of CVD.

- Over 55 million people are exposed to soft water (less than 60 ppm hardness $CaCO_3$ equivalents) in the United States (see Figure 1-1 and Table 1-3).

- The death rate from CVD can potentially be decreased in soft water areas by 0.65 deaths per 100,000 population for each increase of 1 ppm of hardness ($CaCO_3$).

- By increasing the hardness (greater than 60 ppm) through pH adjustment, 13,825 lives could be saved annually in soft water areas. This amounts to a minimum annual health savings of $3.5 billion per year.

- Health benefits from hardening soft water exceed treatment costs by about 300 times.

Corrosion Related Impacts

- Soft water may be corrosive to water distribution systems, leading to significant damage of pipes, pumps, meters, and storage equipment, as well as household plumbing appliances.

- Past studies have shown an increase in certain toxic trace metals from corrosion due to leaching of pipes. These elements, particularily lead and cadmium, can represent a potential health hazard.

- Costs for replacement of water-related pipe corrosion in distribution systems with aggressive water can range up to $20.16 per capita annually, with an average of $2.67 per capita annually.

- Water loss from leakage of pipes in distribution systems can amount to as much as 50 percent. A nationwide water loss average is 15 percent. Of these water losses, 38 percent (equivalent to six percent of distributed water) may be due to corrosion as a result of aggressive water areas.

- Power requirements are higher in many aggressive water areas because of decrease flow capacity in corroded pipes.

Corrosion Control Techniques

- There are two major corrosion control techniques: pH adjustment and addition of corrosion inhibitors.

TABLE 1-2

WATER TREATMENT EFFECTS ON CVD MECHANISMS

	Theory	Treatment Type I	II	III	IV
1a	Calcium lowers CVD.	B	NE	PB	NE
1b	Magnesium lowers CVD.	PB	NE	NE	NE
2a	Lithium beneficial.	NE	PB	PA	PA
2b	Strontium beneficial.	PA	PA	PA	PA
3a	Cadmium related to CVD.	B	B	B	B
3b	Lead related to CVD.	B	B	B	B

NE - No Effect - Treatment will not lower or increase incident of CVD.

B - Beneficial - Treatment will lower incident of CVD.

PB - Potentially Beneficial - Treatment may lower incident of CVD.

A - Adverse - Treatment will increase incident of CVD.

PA - Potentially Adverse - Treatment may increase incident of CVD.

Treatment Types

I - pH adjustment using lime.

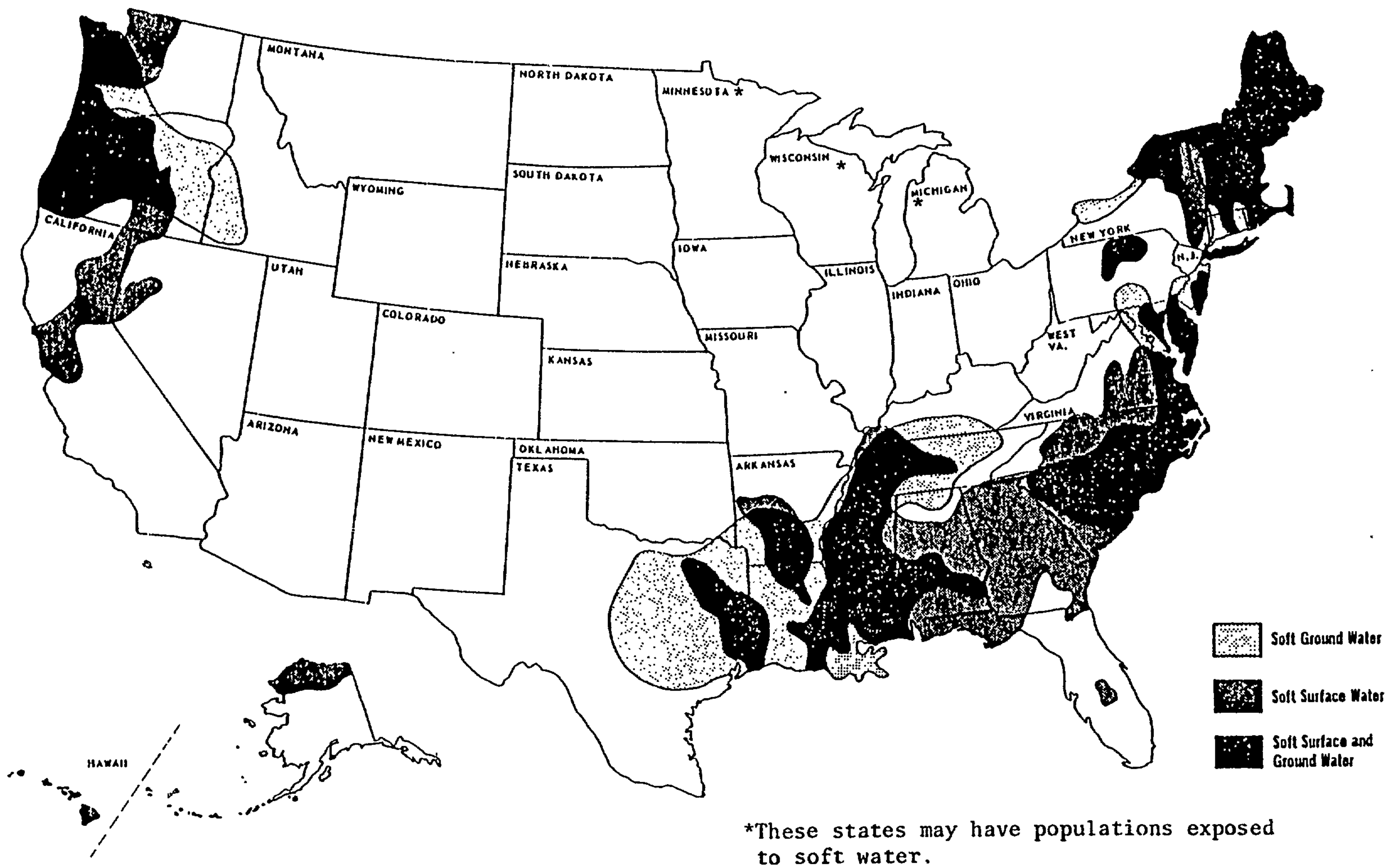
II - pH adjustment using sodium hydroxide or soda ash.

III - addition of corrosion inhibitors - polyphosphates.

IV - addition of corrosion inhibitors - silicates.

FIGURE 1-1

SOFT WATER AREAS IN THE UNITED STATES



*These states may have populations exposed to soft water.

SOURCE: EEA

TABLE 1-5

NUMBER OF PERSONS IN THE UNITED STATES
EXPOSED TO SOFT WATER IN 1970

	Population Exposed (in millions)	Percentage of Population Exposed
Eastern States	30.9	55%
Connecticut	2.9	96%
Delaware	0.5	100%
District of Columbia	0.7	100%
Maine	1.0	100%
Maryland	3.0	78%
Massachusetts	5.7	100%
New Hampshire	0.8	100%
New Jersey	4.5	63%
New York	5.6	31%
Pennsylvania	0.9	7%
Rhode Island	0.9	100%
Vermont	0.4	91%
Virginia	4.0	89%
Southern States	21.4	38%
Alabama	1.0	31%
Arkansas	0.3	17%
Florida	0.1	1%
Georgia	2.7	59%
Kentucky	0.3	10%
Louisana	0.3	8%
Mississippi	2.2	100%
North Carolina	4.4	86%
South Carolina	2.2	83%
Tennessee	2.0	52%
Texas	5.9	53%
Western States	3.7	7%
California	1.0	5%
Hawaii	0.8	100%
Idaho	0.2	23%
Nevada	0.003	0.6%
Oregon	1.5	74%
Washington	0.2	5%
United States	56.0	27%

SOURCE: EEA

- pH adjustment using lime has beneficial health effects.
- Corrosion control by deposition of $CaCO_3$ films on the interior surfaces of the water conveyors provides the broadest and most general protection to water systems and plumbing materials.
- Any of the stability indices, Langlier Saturation Index (LSI), Aggressive Index (AI), or Ranzar Saturation Index (RSI), can be used interchangeably to measure the stability and corrosion potential of water.
- Annual treatment costs to control corrosion range from $0.185 to $0.47 per capita.
- The benefit to cost ratio of using corrosion control to reduce pipe damage ranges from 1.2:1 to 15.4:1.

Regulatory Findings

- EPA has the authority under the Safe Drinking Water Act to regulate soft corrosive water.

1.3 CONCLUSIONS

Soft and/or corrosive water represents a substantial health risk to those dependent on it for drinking water. Several different water treatment methods can lessen the potential adverse health impacts. Technology to decrease water corrosivity is readily available and economically feasible. Not only could the use of this technology result in significant public health benefits, but it could also have the additional benefit of lowering corrosion in public water distribution systems.

EPA has the authority, in the Safe Drinking Water Act, to include a minimum hardness requirement and to establish an MCL based on corrosion indices. This authority should be exercised to protect public health, considering the potential adverse health effects of increased cardiovascular disease in soft water areas and increased toxic contaminants in corrosive water areas. Given the large percentage of the United States population exposed to soft or corrosive water, a minimum hardness requirement and a maximum contaminant level based on any one of the corrosion indices should be implemented nationwide.

2. BACKGROUND

2.1 PURPOSE

For over a decade, questions have been raised over the relation between soft or aggressive water and cardiovascular disease. This concern has been paralleled by extensive research into the role of specific major and trace elements associated with drinking water in health and disease. One purpose of this report is to delineate the issues involved with consumption of soft water, to elucidate postulated mechanisms by which specific elements are implicated in cardiovascular health, and to quantify the public health risks associated with utilization of aggressive water. The ultimate objective of the study is to justify incorporation of aggressive water criteria into the primary drinking water standards based on analysis of available health and epidemiological evidence.

Of obvious concern to utilities is the cost of corrosion control treatment necessary to comply with such an aggressive water standard. However, it has long been noted that aggressive (or soft) water heightens the normal corrosiveness of water, and hence causes early residential pipe replacement, water loss and other types of distribution network maintenance. Thus, this study will evaluate the economic losses sustained by utilities distributing aggressive water and compare these losses with the cost of corrosion control treatments, which can prevent continued corrosion due to aggressive water incidence.

2.2 REGULATORY CONSTRAINTS

The Safe Drinking Water Act (PL 92-523) created two standards for the purpose of protecting public drinking water supplies. Primary drinking water regulations serve to prevent adverse health effects from specific contaminants. Secondary regulations are specified to protect public welfare and address contaminants which affect odor, taste, and other esthetic qualities. States are required to adopt regulations at least as stringent as primary regulations, but adoption of secondary regulations is voluntary. A *contaminant* is defined as "any physical, chemical, biological, or radiological substance or matter in water." Maximum contaminant levels which satisfy the objectives of primary and secondary regulations are established by the U.S. Environmental Protection Agency (EPA).

With respect to the possible inclusion of corrosivity into the Primary Drinking Water Regulations, two salient legal constraints must be considered. The first concerns the definition of corrosivity or water softness as a contaminant. The second addresses the legality of a chemical addition requirement in the national drinking water regulations.

Although corrosivity already is included in the secondary drinking water regulations, the adverse health risks associated with use of soft water dictate the adoption of a primary corrosivity and/or hardness standard as well. Since water hardness is related inversely to cardiovascular disease and corrosivity, the primary regulation should be in the form of either a minimum water hardness standard or a maximum corrosivity standard. Since the Act provides for only the regulation of contaminants, it is necessary to characterize water hardness and/or corrosivity as water contaminants. Although neither is a "substance" per se (rather, characteristics attributed to a number of chemical conditions), water hardness and corrosivity can still be admitted under the equivocal definition of contaminants due to their demonstrated adverse effect on public health. Further, the Interim Primary Regulations established the precedent for a broad interpretation of the term "contaminant" in its determination of turbidity as a contaminant.

Another legal factor impinges upon chemical addition, which is necessary to stabilize soft water and mitigate associated health effects. Under Section 1412(b)(6), National Primary Drinking Water Regulations cannot require chemical addition for preventative health purposes unrelated to water contamination. This provision was originally intended to preclude use of the Act as a vehicle for interest of fluorination or other preventative health care substances. However, since the addition is due to the presence of an influent contaminant (corrosivity) and not "unrelated to water contamination", the intent of this provision will not be violated if chemical addition is required for stabilization of soft water.

2.3 DEFINITIONS

Water Chemistry Terminology

Throughout the report, water will be referred to as soft, aggressive or corrosive in nature. Although these terms are not synonymous in all instances, they will be used interchangeably for the purposes of this study. Brief definitions of each term are presented below.

Corrosive or Aggressive Waters - These two terms are synonymous. The primary characteristic of these waters is their ability to induce electrochemical corrosion on metal surfaces. Several chemical characteristics of the water define the rate at which corrosion occurs including pH, alkalinity, and hardness. Extrinsic factors such as temperature and dissolved oxygen content affect corrosion rates as well. Three indices are used to estimate the corrosion potential of water, generally by predicting the solubility potential of $CaCO_3$. Deposition of $CaCO_3$ forms a scale on surfaces which dramatically reduces corrosion. The three indices are Langlier Saturation Index (LSI), Aggressivity Index (AI), and the Ryznar Stability Index (RSI). Aggressive water is indicated respectively by values less than zero, less than 12, and greater than 7.0.

Soft Waters - Water hardness is a measure of the concentrations of calcium and magnesium. Approximately one percent of water hardness is attributable to trace cations such as aluminum, iron, maganese, zinc, and strontium. Because all corrosivity indices are strongly affected by water hardness, aggressive or corrosive water, as judged by these indices, is roughly equivalent to soft water. To remain consistent with the various sources used in the report, a cutoff point of 60 ppm hardness expressed as $CaCO_3$ will be used to distinguish hard water (greater than 60 ppm) from soft water.

Cardiovascular Disease Classification

In order to clarify the medical terminology used in this report a descriptive breakdown of disease categories is provided below:

Coronary heart disease - coronary heart disease (CHD) is a condition whose underlying pathology is arteriosclerosis. Arteriosclerosis involves the loss of elasticity of arterial walls accompanied by thickening and hardening of these walls. When this occurs in the coronary arteries which supply the heart, involving the inner lining of these vessels, it is referred to as atherosclerosis. This condition is initiated by deposition of fatty substances in the arterial walls which then evolve into "plaques." Ulceration, calcification, and sometimes hemorrhage and accumulation of thrombi (blood clots) follow. The net effect is that the affected arteries become constricted, and thus progressively smaller in diameter. This leads to a reduction in the supply of oxygen to the heart muscle area that is normally fed by the affected artery. The involved area of heart muscle may actually die, the size of the infarct area being proportional to the size of the artery affected.

The infarct area is then replaced by the body with nonfunctional fibrous material, essentially reducing the functional capacity of the heart. Coronary heart disease is the predominant form of heart disease, accounting for more than fifty percent of all CVD deaths. CHD can be further subdivided into the following subclasses:

- Myocardial Infarction - commonly known as a "heart attack" resulting from thrombosis of the coronary artery. One-fifth of all heart attacks (infarcts) lead to immediate sudden death.

- Angina Pectoris - occasional chest pain resulting from slightly decreased supply of blood to the heart muscle.

- Coronary Ischemia/Ischemic Heart Disease/Coronary Insufficiency - persistant anginal pain resulting from a significantly reduced supply of blood to heart muscle.

Hypertension - elevated blood pressure above normal levels leading to:

- Hypertension Heart Disease - any cardiac abnormality observed in association with hypertension.

- Hypertensive Vascular Disease - extracardiac vascular disease (e.g., cerebrovascular) associated with hypertension.

Cerebrovascular Disease - commonly known as stroke or apoplexy. This disease is second only to CHD as a cause of cardiovascular death, having caused 11 percent of the CVD mortality in 1966. Cerebrovascular disease can involve aneurysms (small sacs of clotted or unclotted blood extending outward from a damaged blood vessel toward surrounding tissue) which may burst, leading to hemorrhage and often death. Conversely, it may involve construction by plaque growth of major arteries that supply the brain, leading to severe effects that are usually complicated by thrombosis. This can occur in both hypertensive and non-hypertensive persons. Another form of cerebrovascular disease involves sudden obstruction of blood vessels in the brain with a blood clot (embolism). This is often a secondary complication to rheumatic heart disease or to atherosclerotic coronary heart disease.

Rheumatic Heart Disease - an inflammatory disease that accompanies infection with hemolytic Streptococcus bacteria (group A). The exact mechanism is uncertain, but may involve an altered immune response that is directed against heart muscle tissue.

2.4 DATA SOURCES

EEA collected information concerning aggressive water from its own files, from the Midwest Research Institute, and from the A/C Pipe Producers Association. Various manufacturers of corrosion control chemicals were contacted in regard to chemical prices, utilization and effectiveness. These manufacturers included Philadelphia Quartz Company, Diamond Shamrock Chemical Company, and Calgon Corporation.

EEA obtained all relevent epidemiological studies relating drinking water and cardiovascular disease using a computer-assisted literature search carried out at the National Library of Medicine. Dr. Cecil Slome, faculty member of the Department of Epidemiology in the School of Public Health at the University of North Carolina aided in the evaluation of existing epidemiological studies. Dr. Slome is an assistant to Dr. H. Tyroler, a noted expert in the study of soft water and heart disease.

Further, EEA elicited the services of the Rockburn Institute in Baltimore, Maryland in clarifying and reviewing the possible mechanisms relating soft water to cardiovascular disease.

A selected group of studies used to quantify the relationship between water quality and death rates is presented in more detail in Section 3.4.

3. HEALTH RISKS OF SOFT WATER

3.1 INTRODUCTION

3.1.1 Overview

Cardiovascular disease (CVD) results in the death of approximately 1,000,000 people annually in the United States, and accounts for 50 percent of total deaths from all causes. The toll from CVD is the heaviest among the aged, as 50 percent of the victims are older than 65. The major cardiovascular diseases of concern to the possible involvement of soft water are coronary (arteriosclerotic) heart disease, cerebrovascular diseases, hypertension, and hypertensive heart disease. These diseases vary in etiology, age of onset, clinical course, and mortality characteristics. Figures 3-1 and 3-2 present incidences and mortality rates, respectively, for various cardiovascular diseases. In this section, we will examine the mechanisms by which soft water is related to CVD, the epidemiological studies which support or refute these mechanisms, and the health costs to the exposed population.

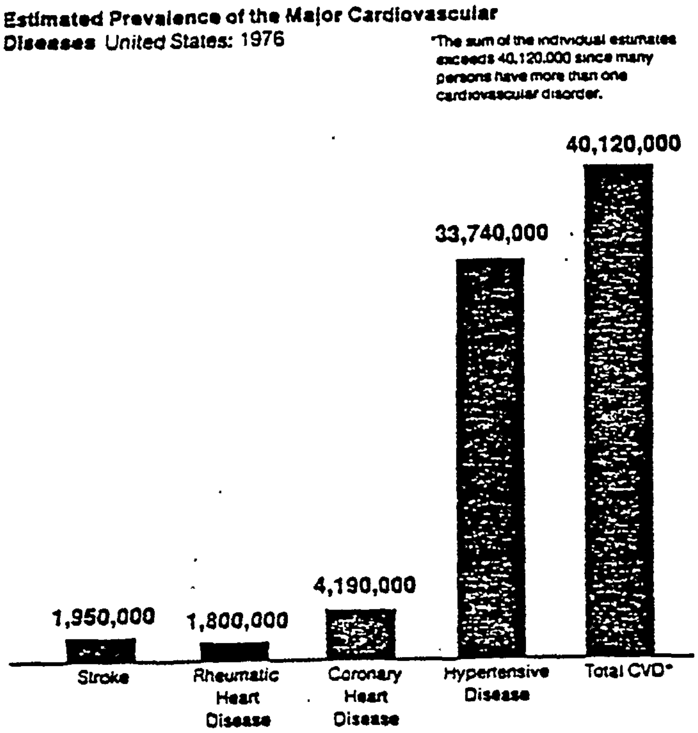
3.1.2 Risk Factors Involved in Cardiovascular Disease

The average American male has a 20 percent chance of suffering a heart attack and a 10 percent probability of dying of cardiovascular disease before the age of sixty. Many potential victims remain undetected until such an episode occurs, or if diagnosed, are detected too late to reverse the progression of the disease.

Clearly the strategy to use against heart disease is prevention. Preventive measures must be targeted at the known risk factors involved in the initiation of CVD (causal factors) and those factors involved in the

FIGURE 3-1

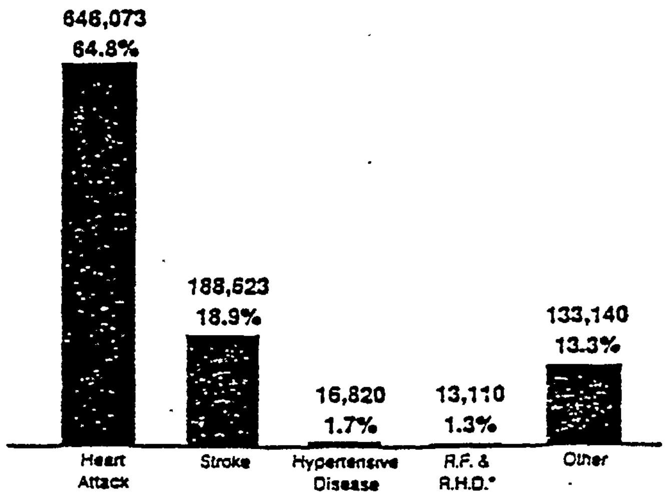
Estimated Prevalence of the Major Cardiovascular Diseases United States: 1976



Source: American Heart Association

FIGURE 3-2

Deaths Due to Cardiovascular Diseases by Major Type of Disorder United States: 1976



*Rheumatic Fever and Rheumatic Heart Disease

Source: National Center for Health Statistics, USPHS, DHEW progress of CVD (promoting factors). A summary of CVD risk factors is listed in Table 3-1 and their significance for heart disease is summarized in Table 3-2. Specific factors may be associated with some types of cardiovascular disease and not with other types. Furthermore, some of these factors may be additive, synergistic, or antagonistic with other risk factors. The impact of soft drinking water is undoubtedly additive or synergistic with some of the other CVD factors. It is interesting to note that, excluding drinking water, all known risk factors account for only 50 percent of the incidence of cardiovascular disease. Drinking water may well account for a significant fraction of the remaining 50 percent.

3.2 POSSIBLE MECHANISMS

Soft water may be involved in an adverse manner with cardiovascular disease by one or a combination of more than one scenarios. It is not certain whether soft water parameters (factors) initiate heart disease, whether soft water added onto other factors which predispose the person to CVD is sufficient to push him or her over the threshold to symptomatic illness, or whether the condition of a person who already suffers from the disease overtly (with recognizable symptons) or asymptomatically (without recognizable symptoms) is significantly worsened by consumption of soft water. It is likely that several, if not all, of the above scenarios occur.

Soft water may be associated in a causative or detrimental manner with CVD by one or several of three postulated mechanisms which may operate within one or several of the above scenarios. Class 1 mechanisms involve major cations that are protective toward the cardiovascular system and that are abundant in hard water, but deficient in soft water. Class 2 mechanisms involve protection of the cardiovascular system by specific minor cations or trace metals that are present in higher concentrations in hard water than in soft water. Class 3 mechanisms involve leaching

TABLE 3-1

RISK FACTORS FOR CARDIOVASCULAR DISEASE

Age	Hemodialysis
Blood pressure	Male sex
Cigarette smoking	Metabolic factors
Dietary factors	Diabetes mellitus
Lipids	Gout
Sucrose	Homocystinemia
Coffee	Obesity
Water	Oral contraceptives
Ethanol	Psychosocial factors
Environmental factors	Sedentary living
Air pollution	Viruses
Radiation	
Noise	

TABLE 3-2

SIGNIFICANCE OF SOME SELECTED CARDIOVASCULAR DISEASE RISK FACTORS

Risk Factor	Disease	Comments
Drinking Water	Various CVD	Negative correlation of CVD with water hardness. Negative correlations or positive correlations for specific metal cations.
Cholesterol	CHD	Evidence for this factor in terms of animal experiments and epidemiology indicates that a man with serium cholestrol ≥ 250 mg/100 ml has a 3-fold excess risk of heart attack, although recent references infer that dietary fatty acids may be more important.
Blood Pressure	Stroke, Arteriosclerosis	High blood pressure links coronary atherosclerosis (the lesion) to coronary heart disease (the clinical disease). Strong support from animal data. Also, strong factor in stroke. A man with systolic pressure >150 has 2-fold excess risk of heart attack and 4-fold excess risk of stroke.
Obesity	Various CVD	Good evidence.
Sucrose	Various CVD	Sugar is a factor in that high sugar consumption often leads to obesity. Its direct biochemical/physiological implications for CVD are still unestablished.
Smoking	CHD	Good evidence, especially for males 35-55 yrs. A one pack-per-day smoker holds a 3-fold excess risk of CHD. Especially strong correlation for sudden death. Cigarette smoking increases carboxy-hemoglobin levels (decreases the oxygen carrying capacity of the blood) and affects catecholamine levels and platelet adhesiveness.

TABLE 3-2 (Continued)

SIGNIFICANCE OF SOME SELECTED CARDIOVASCULAR DISEASE RISK FACTORS

Risk Factor	Disease	Comments
Diabetes Mellitus	CHD	Excessive CHD rate in diabetics is well-established. Diabetics hold a 3-fold excess risk if remale, 2-fold excess risk if male.
Sedentary Living	Various CVD	Exercise has been shown to be beneficial.
Air Pollution	Various CVD	Primary mechanism is through formation of carboxy-hemoglobin. Somewhat speculative.
Oral Contraceptives	Fatal/Nonfatal Myocardial Infarction	Increased risk for women on the pill. This effect is independent of other factors, although synergism with additional factors does occur.
Coffee	CHD, especially acute Myocardial Infarction	Positive correlation, but it is difficult to separate it from other causes. May reflect psychosocial factors.
Psychosocial Factors	CHD	"Type A" behavior. People with abnormal sense of time urgency. May act through catecholamine levels, clotting factors, or cardiac electrophysiology.

of toxic metals which are deleterious to human health from drinking water distribution systems in the presence of soft water. Table 1.1 categorizes some common metal cations by mechanism class. These metals are discussed below with regard to possible cause and effect mechanisms.

3.2.1 Class 1 Mechanisms

There are two cations implicated in this mechanism -- calcium and magnesium. Water hardness relates almost directly to calcium and magnesium concentrations. Thus, epidemiological studies that demonstrate an association between water hardness and heart disease may really be making a connection between one or both of these two cations and CVD.

3.2.1.1 Magnesium

Some of the best evidence for a metal cation role in heart disease exists for magnesium. In addition to the older literature, several recent publications cite magnesium as a strong factor in cardiovascular health. In fact, European physicians who have used magnesium salts as a protective agent for heart patients report a considerably enhanced survival rate.

Magnesium is an essential element for man. Deficiency of this metal results in neuromuscular disorders, calcification, and cardiac and renal damage. Magnesium is a cofactor of many important enzymes, especially those which utilize adenosine triphosphate (ATP), a biochemically-universal molecule used for chemical storage of energy. Such enzymes are found in abundance in heart muscle, and are essential for heart function (muscle contraction).

Some persons may suffer a marginal deficiency in magnesium. Those who are poor or elderly are those nutritionally at risk of magnesium deficiency due to dietary ignorance, apathy, or a limited food budget which discourages purchases of good sources of magnesium (nuts, meat, seafood, green-leafy vegetables, vitamin/mineral supplements). In this high-risk group, magnesium intake in drinking water may represent as much as 50 percent of the daily intake. Thus, these subpopulations that have low nutritional status may be at high risk of CVD if they are drinking soft water. The importance of drinking water as a source of magnesium is supported by the observation that human serum magnesium concentrations (U.S.A.), bone magnesium levels (United Kingdom), and heart muscle magnesium levels (Canada) are lower in soft water cities or regions than in hard water cities or regions.

In addition to magnesium deficiency due by dietary insufficiency, people exposed to hard physical labor under high temperature conditions lose a large proportion of the body supply of magnesium through perspiration. Also, persons with maladsorption problems, renal diseases, or those taking diuretics lose a considerable amount of magnesium daily. All of these subpopulations are potentially high-risk groups for CVD if they are drinking soft water.

The mechanisms by which magnesium could be related to heart disease are three-fold. The first, as alluded to above, is that deficiency in magnesium could cause abnormal heart muscle function, leading to arrhythmia and other cardial malfunctions. Secondly, decreased magnesium balance in the body can result in calcium deposits in tissues, including arteries. These deposits may be precursors for arteriosclerotic plaques. Furthermore, those persons with low magnesium balance have decreased clotting time, and therefore may also demonstrate an increased incidence of coronary thrombosis.

3.2.1.2 Calcium

It is unclear whether waterborne calcium is absorbed in the intestine any more efficiently than dietary calcium, or whether calcium supplied from drinking water can play a significant role in calcium balance. Nevertheless, some interesting mechanisms for the involvement of calcium in cardiovascular disease have been generated.

Calcium is present in the body in larger amounts than any other mineral element. The body of an adult male weighing 70 kg contains approximately 1.2 kg of calcium, 99% of which is in the skeleton as calcium phosphate. The most plausible mechanism centers around the role of calcium in muscle function. Calcium is vital to muscle function, being transported intracellularly by an ATP-dependent system, being accumulated in membranous intracellular organelles called mitochondria and endoplasmic reticulum during the resting stage of muscle, and then released into the cytoplasm (cell fluid) to initiate firing of the muscle. Calcium deficiency could upset the calcium balance in heart muscle, leading to arrythmia. Furthermore, calcium in concentrations within the cell regulate a large number of cellular biochemical activities and most protein hormones are inhibited in the absence of calcium.

Calcium may act by its effect on zinc binding (calcium reduces zinc absorption) leading to decreases in serum cholesterol levels and to beneficial effects on elastin and collagen incorporation into arterial walls. Calcium may also act by blocking absorption of cadium and lead, the former of which is known to cause hypertension at parts-per-million levels in drinking water.

3.2.2 Class 2 Mechanisms

3.2.2.1 Lithium

Lithium occurs in nature primarily as the silicate. The average daily human intake is 3-4 mg. Lithium is readily absorbed from the gastro-intenstinal tract. Daily water intake of lithium exceeds that obtained through foods, lithium concentrations in hard water being much higher than that in soft water. On a biochemical level, lithium blocks release and reabsorption of the neurotransmitter norepinephrine, thus reducing nerve transmission at affected axons. It also inhibits the neurotransmitter serotonin by inhibiting the enzyme that synthesizes it. Lithium has known and established beneficial influence on four heart disease factors. Lithium reduces hypertension and reduces serum lipid concentrations. Furthermore, it reduces the risk of heart disease as a complication of diabetes mellitus. Furthermore, lithium reduces the stress-induced type A manic behavior, which is characterized by high-competitiveness and an abnormal sense of time urgency.

3.2.2.2 Chromium

Chromium is an essential element for man, drinking water providing 10 to 40 percent of the average daily intake. Trivalent chromium plays an important role in glucose and lipid metabolism. Some studies indicate that trivalent chromium is an essential factor for promoting insulin-mediated utilization of glucose. Glucose is one of the raw materials used for production of ATP, which is the source of energy for normal heart muscle function. A chromium deficiency, then, could potentially produce arrythmia.

A chromium deficiency also produces diabetes mellitus and aortic plaques in rats. Several medical reearchers have noted the importance of chromium deficiency as a basic factor in the development of atherosclerosis. As further support for this, the addition of chromium to the diet of male rats lowers their serum cholesterol. This is understandable in a biochemical sense, since chromium sufficiency would promote utilization of glucose for ATP production and, therefore, reduce the amount of glucose being converted to lipids and cholesterol. Thus, chromium may be cardioprotective for humans. Interestingly, a deficiency of trivalent chromium increases the toxicity of lead.

3.2.2.3 Manganese

Manganese is an essential trace element that is an important cofactor in many enzymes. Manganese is required for normal bone structure, reproduction, central nervous system function and heart function. Manganese consumed in drinking water can represent between less than one percent to up to fifty percent of the daily intake of this element. The turnover of manganese in the human body is rapid, and therefore this element needs replenishing on a daily basis.

The high concentration of manganese in heart tissue is reflected by the increase in serum manganese that occurs immediately after a myocardial infarct (heart attack). Manganese is important in normal mitochondrial function and, therefore, in the production of ATP for normal heart muscle function. Additionally, manganese is essential for insulin production, and thus for normal glucose metabolism. Manganese deficiency produces a diabetes-mellitus-like syndrome in guinea pigs, which is accompanies by greater than normal production of triglycerides and cholesterol as reflected by their serum concentrations. Thus, one can implicate a role for manganese in protection of man from CVD through control of lipid metabolism, lipids being a well-known risk factor for man.

3.2.2.4 Selenium

Selenium is an essential element whose mechanism in protecting man from cardiovascular disease is not clear. In very small quantities selenium may be a factor in tissue respiration (and thus production of ATP) but its significance relative to other factors which affect this is uncertain. Selenium also plays a role which parallels Vitamin E's role in sequestering toxic oxygenated radicals in tissues. Thus, selenium may play a role in reducing oxygen toxicity in heart muscle tissues.

3.2.2.5 Vanadium

Vanadium is an element whose requirement for human metabolism and nutrition is presently undetermined. Vanadium is a ubiquitous element, and it is not clear that hard drinking water can supply a significant amount relative to dietary intake. Its role in protecting man from CVD may be to its ability to decrease cholesterol and phospholipid production.

3.2.2.6 Strontium

There is some evidence that strontium is essential for calcification of bones and teeth. Biological evidence suggests that strontium may protect man from CVD by involvement in electrocardiological function and, speculatively, in possible prevention of calcification of atherosclerotic plaques. The relative contribution of drinking water to the daily intake of strontium is not known.

3.2.3 Class 3 Mechanisms

3.2.3.1 Cadmium

The toxic metal cadmium can be leached from certain types of pipe lines in the presence of aggressive water. There is strong evidence for cadium being a factor in cardiovascular disease. Cadmium has been shown to induce hypertension in experimental animals, and it occurs in abnormally high concentrations in hypertensive people. An elevated cadmium concentration and cadmium/zinc ratio has been observed in tissues of patients who died of hypertensive complications compared to those who died of other causes. Cadmium and zinc interact, zinc being able to reverse cadmium-induced hypertension in laboratory animals.

Cadmium accumulates in many tissues, preferentially in the kidney. On a biochemical level cadmium interferes with zinc binding (by competitive binding) to essential enzymes that require zinc. Cadmium also interferes with calcium metabolism, which could interfere with normal heart muscle function (see Section 3.2.1.2). Cadmium has also been shown to depress normal electrical impulse transmission to the heart by obstructing conduction or by altering cell excitability. Cadmium also increases salt resorption and retention by the kidneys, which accounts for its effects on hypertension. Interestingly, high doses of cadmium produce toxic effects without producing hypertension.

3.2.3.2 Copper

The biological function of copper, which is an essential trace element, is not completely understood. There is no shortage of copper in dietary intakes in the United States, the daily requirement being 2.5 mg for adults. Contact of copper pipes with soft water can increase the daily intake of copper by as much as 2.0 mg/day. This may represent an intolerable excess as the border between copper deficiency and copper toxicity is narrow. Some individuals are quite sensitive to the toxic effects of copper, showing adverse effects with intakes of even small amounts of the element.

The serum concentration of copper, which reflects the daily intake, determines the effects. A minimum level of copper is needed to supply the element to important oxidative enzymes such as cytochrome oxidase, which utilize it as a cofactor in production of ATP as an energy supply for normal heart muscle contractions. An excess level of serum copper in elderly people has been associated with atherosclerosis. Copper may accelerate the development of this disease. Additionally, high serum copper concentrations will cause accumulation of copper in the kidney, resulting in damage to the renal tubules, and increased excretion of electrolytes and other factors necessary for normal heart function.

3.2.3.3 Lead

The lead content of water can be increased by leaching of lead from pipe or pipe-joining materials, thus producing lead concentrations at the tap which may exceed the drinking water standards. The body burden of lead in Americans is twice that of people living in underdeveloped countries. Drinking water can represent up to one-third or more of the daily intake in the United States.

Lead is not an essential element and since it accumulates in the body, any excess intake represents an additional risk. Lead is weakly correlated with cardiovascular disease. The mechanism for its involvement in CVD is unknown. The lead concentration in heart muscle tissue in CVD victims in soft water areas is higher than that in those from hard water areas. Interestingly, animal studies indicate that the toxicity of lead at a given concentration is higher in animals given hard water as opposed to animals given hard water. Persons with marginal zinc deficiencies may be more sensitive to lead exposure.

3.3 EPIDEMIOLOGY: SUPPORT FOR THE RELATIONSHIP BETWEEN CARDIOVASCULAR DISEASE AND SOFT WATER

Epidemiological studies have been conducted to determine whether there is a link between soft water and heart disease. Although there has not been complete agreement between these studies, the data are sufficiently strong to suggest that soft water is detrimental to cardiovascular health. It is important to remember that what is being demonstrated by these studies is an association and not cause and effect.

There are basically three types of studies undertaken in epidemiology. These are described as retrospective, prospective, or intervention studies. Retrospective studies, sometimes called case-control studies, connect information concerning past events by direct inquiry of respondents. Basically such studies look at the association of past events with recorded or current illness. Prospective studies investigate and categorize a sample of individuals by one or several factors and then follow them over a period of time necessary to observe the occurrence of disease among both groups. Such studies serve as a better and more direct test of a hypothesis than retrospective studies, although prospective studies require more investment of resources. Intervention studies are planned studies, with appropriate controls, which alter the exposure to presumed etiological factors (or introduce some form of prevention) and then quantifies the influence of this change.

Most of the studies that have been published in the epidemiological literature have been retrospective studies. No planned community intervention trials have been published. There have been numerous original articles and review articles concerning this subject since the original Kobayashi paper of 1957 which linked high stroke mortality with corrosive (soft, acidic) river water in Japan.

The conclusions drawn from examining the existing studies are that:

1. There is considerable evidence supporting the existence of a relationship between soft water and heart disease.

2. A great number of major and trace elements, singly or in combination, have been suggested as the factor involved in this relationship. For some there is good observational and/or biochemical evidence.

3. There is enough biochemical support to implicate one or many risk factors for disease morbidity or case fatality or both.

4. The findings that water hardness is not related consistently to other known risk factors for cardiovascular disease does not negate its possible independent or additional action, or its involvement in the lethality of an adverse cardiovascular event.

5. Insufficient evidence exists to indicate which mechanism is most important, but calcium, magnesium, and cadmium are strong possibilities.

6. When large units of study are involved, e.g., nations, states, regions, the association is usually found to hold, but when smaller units of study are selected, the association is often weak and not statistically significant. By pooling large geographic areas, one

can reveal important trends. However, the advantage of smaller unit studies is that there is less heterogeneity of independent variables (water quality parameters) or of confounding variables, and less likelihood of invalid death certification.

7. No studies have addressed nor used indices of dosage and duration of exposure to water.

8. Many studies do not correct for important confounding variables.

9. The fact that a negative correlation between water hardness and CVD mortality rate is not seen universally in all studies indicates that in some geographic areas factors other than water hardness, e.g., diet, are overriding. For example, some soft water areas may be compensated by adequate amounts of the missing element (e.g., calcium, magnesium) in the diet, and some hard water areas may have higher than expected cardiovascular disease due to high salt consumption.

3.4 INCREASED CVD CAUSED BY SOFT WATER

In the majority of epidemiological studies, significant levels of correlation were found. However, few of the studies attempted to quantify the actual magnitude of the impact which water hardness has on the CVD death rate.

In order to assess the health impact of increased drinking water hardness, it was necessary to develop an estimate of the functional relationship between hardness and death rate. As a basis for this determination, data from three published studies were used in parallel with an in-house study based on published death rates and chemical analyses of drinking water in the State of Wisconsin.

The published studies that were selected for the analysis were chosen because they provided adequate data to conduct the requisite analyses and were judged to be procedurally and statistically acceptable. However, the studies, like all other studies to date, are not totally definitive. No published work has yet controlled for all social and environmental variations within the studied population nor for all confounding health variables. Indeed, it may not be possible to construct a perfectly controlled study of the environmental factors affecting the incidence of CVD. However, within the limitations of current data, the most valid conclusion that can be reached is that soft water does have an impact on the rate of CVD and that the impact is on the order shown by the analysis described below.

The first source employed in this analysis compared six hard water and six soft water towns in England and Wales (Stitt, 1973). The data used were hardness of tap water measured in ppm and published CVD death rates between 1958 and 1964. The definition of death from CVD corresponded to ICD numbers 393 and 458 inclusively. The data used was gathered as an aside to the principal purpose of the Stitt study which was to compare clinical parameters among similar individuals in the different towns. Significantly higher blood pressure, heart rate, and plasma-cholesterol were found in a sample of civil servants in the soft water towns than in a corresponding sample from the hard water towns which was matched for age, weight, and percentage of smokers. The study had a sample size of 489.

The second source of data was a study conducted by Margaret Crawford, et. al., (1968) of 61 county boroughs of England and Wales. The boroughs all had populations in excess of 80,000. Hardness was measured at the tap. Death rate was studied separately for two age classes (45-64 and 65-74) and for both sexes. The analysis was based on 1961 data.

The third source of data was a study conducted by J.N. Morris on the hardness of local water supplies and the mortality rate from cardiovascular diseases. The male age group examined was from 45-64.

To supplement the published studies, EEA undertook an effort to develop a measure of the impact of hard water based on a large sample of U.S.

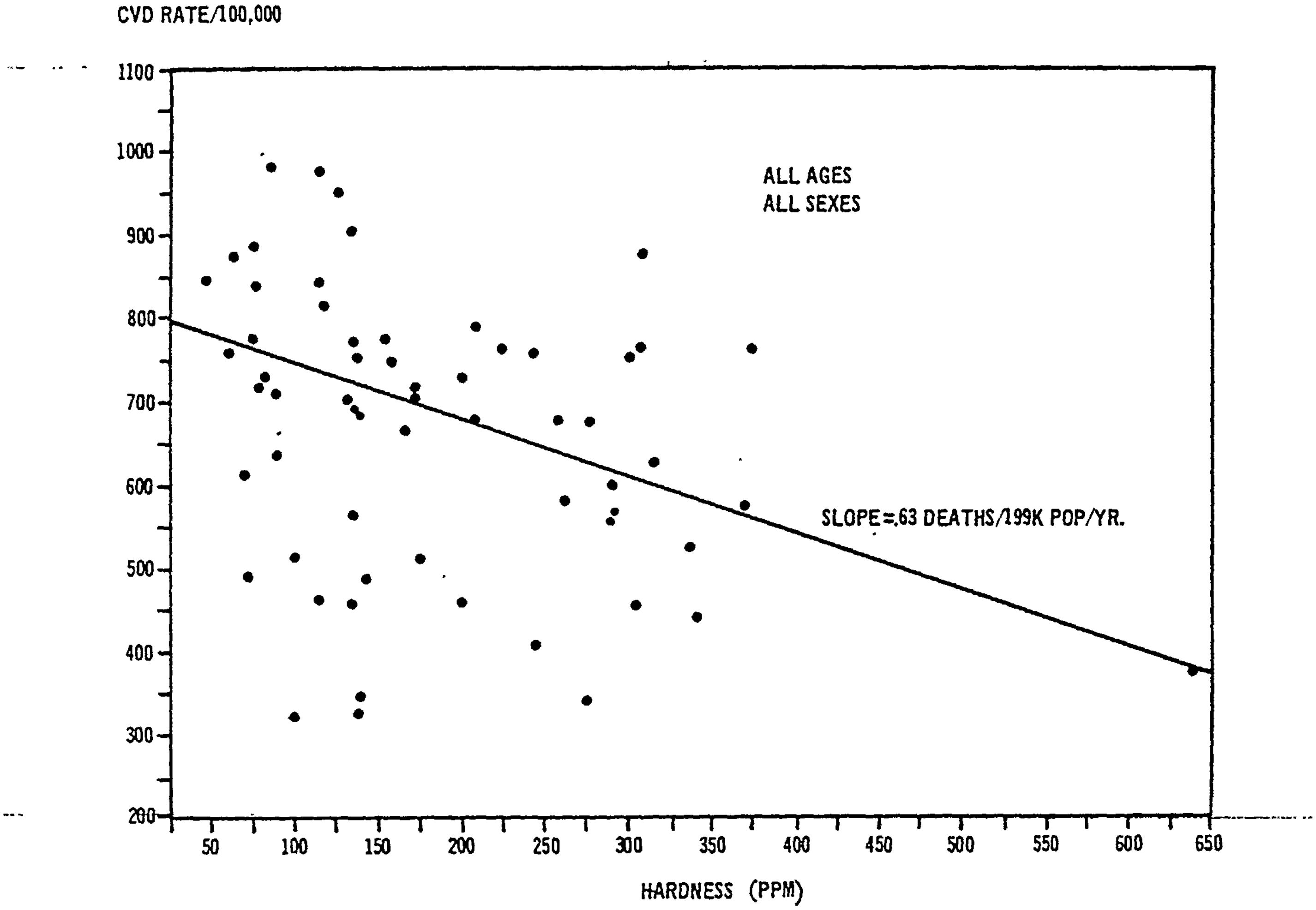
data, covering the full range of hardness experienced in U.S. municipal water supplies. For this purpose, data from Wisconsin were used. A detailed survey of minerals in tap water for sixty-six towns was available for this study (Baumeister, 1972). Death rates and population data were obtained from the United States Census. The limitations of using census data are well known. These are largely offset by the large sample size, the relative similarity of the size of the towns used in the study, and the general homogeneity of the populations. The range of hardness over so small a geographic area is a uniquely valuable opportunity for an assessment of this sort.

Graphs of the data from all four studies and the regression lines obtained are shown on the following pages. The rate of death from cardiovascular disease is plotted on the vertical axis. The unit of measure is deaths per year per 100,000 exposed population. Hardness in parts per million is plotted on the horizontal axis. The plots based on published studies are for males, ages 45-64. The plot of the EEA/Wisconsin data is for the entire age population.

In 1976, males between the ages of 45 and 64 were about 1.62 times more likely to die of heart disease than the population as a whole. Assuming that the effect of hard water is not a function of age and sex, this implies that EEA's whole population estimate of .63 deaths per year per 100,000 is equivalent to a rate of about 1.02/year/100,000 for males between 45 and 64. This is in excellent agreement with the published British studies.

Though the regressions resulted in coefficients at the 95 percent level of significance, it must not be inferred that a change in the hardness of drinking water in a distribution system will immediately experience a change in the death rate. The coefficients simply indicate that the CVD death rate would have been lower by the indicated amount had the popula-

FIGURE 3-3
EEA/WISCONSIN MAJOR CVD
REGRESSION ANALYSIS



SOURCE: EEA Wisconsin Data

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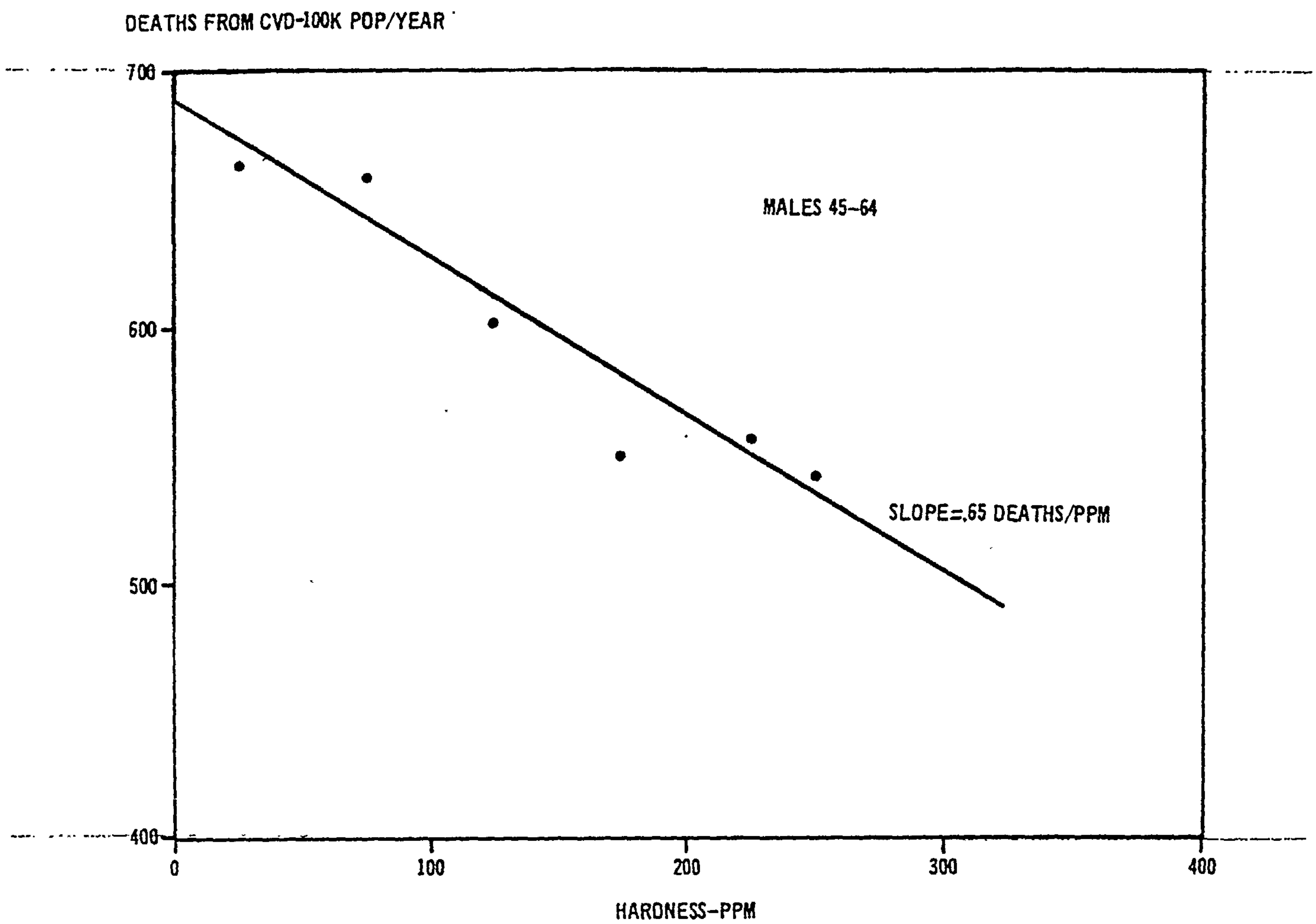
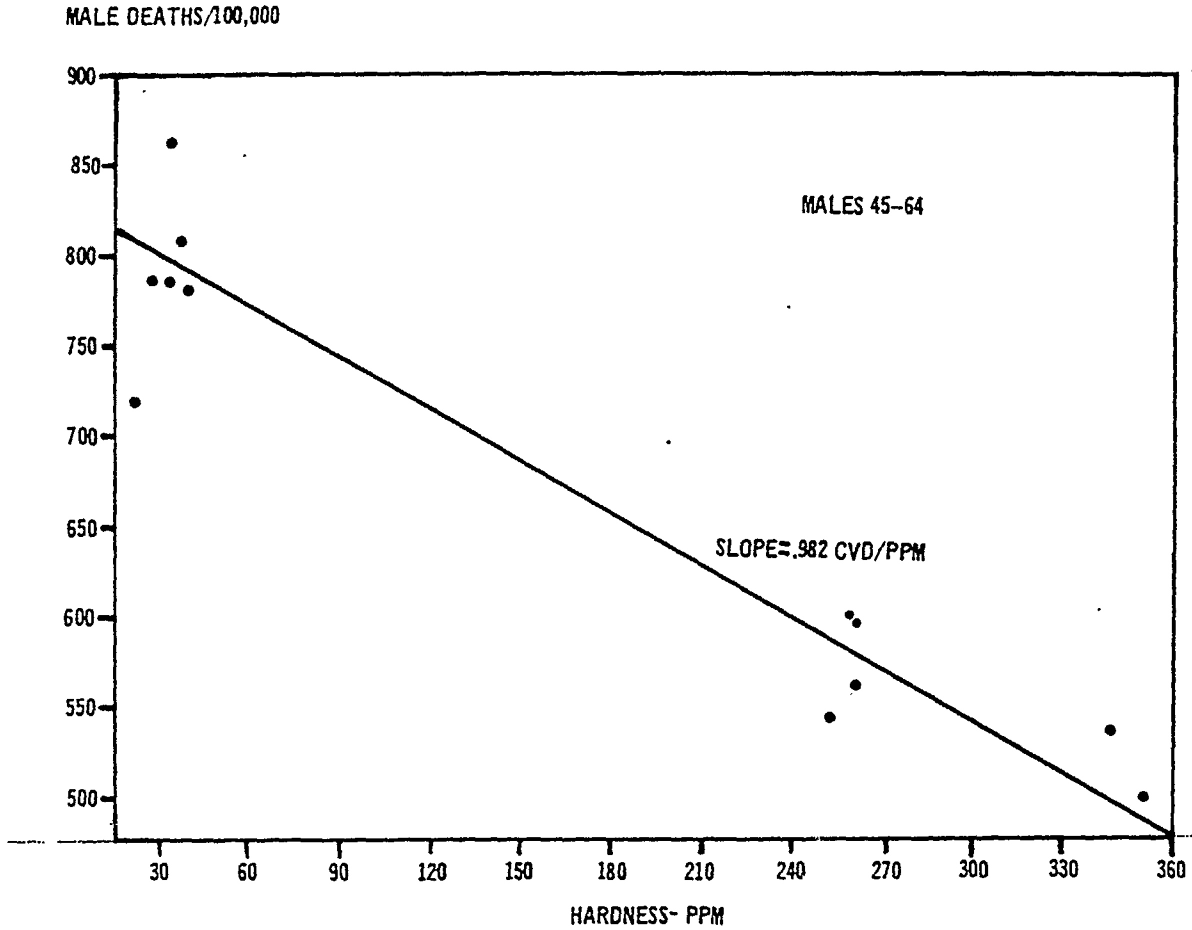
FIGURE 3-4
MORRIS: HEART DISEASE
REGRESSION ANALYSIS



SOURCE: Morris, J. N.,et. al. "Hardness Of Local Water-Supplies And Mortality From Cardiovascular Diseases," The Lancet, April 22,1961, pp. 860-862.

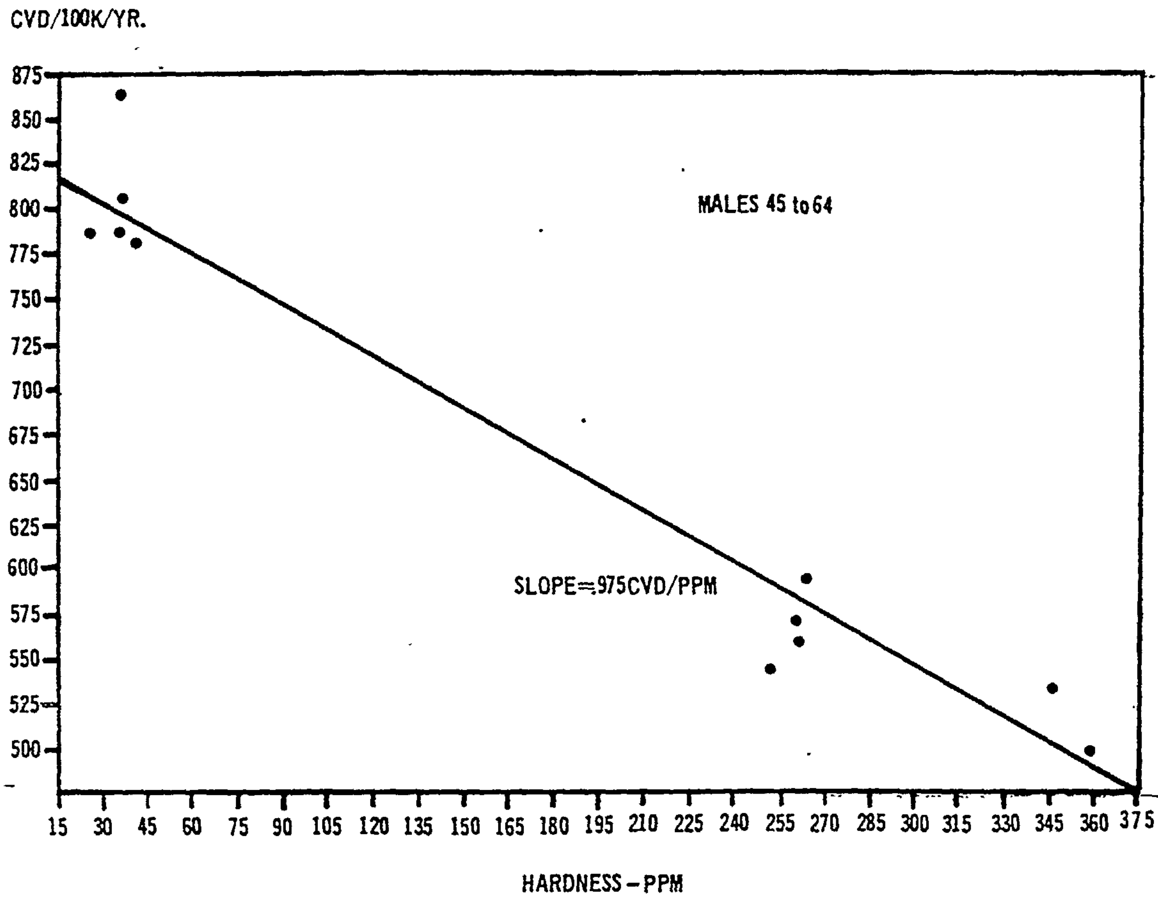
FIGURE 3-5

STITT: SUDDEN CARDIAC DEATH
REGRESSION ANALYSIS



SOURCE: Stitt, F. W., et. al. " Clinical and Biochemical Indicators Of Cardiovascular Disease Among Men Living In Hard And Soft Areas, " The Lancet, January 20, 1978, pp. 122-125.

FIGURE 3-6
CRAWFORD: SUDDEN CARDIAC DEATH REGRESSION ANALYSIS



SOURCE: Crawford, Margaret D., et. al, "An Epidemiological Study Of Sudden Death In Hard and Soft Water Areas," Journal of Chronic Disorders, Vol. 30, July 30, 1977, pp. 69–80.

tion been exposed to harder water over a long period of time. There is no evidence at this time on which to base any inference regarding the short term impact of changes in water hardness or the effect of exposure to water of varying hardness during a lifetime (refer to Table 3-3 and Figure 3-7).

It is necessary to restrict the interpretation of the regression coefficients further by noting that there is still a high degree of uncertainty regarding the mechanism relating water hardness to CVD. It is quite possible that some techniques for hardening water may have no positive effect in this regard.

3.5 HEALTH BENEFITS OF WATER TREATMENT

3.5.1 Introduction

Water treatment techniques currently exist which increase water hardness and reduce metal leaching from distribution network surfaces. By implementing these technologies, potential health risks associated with soft water may be decreased. As discussed previously, there are various theories correlating harmful constituents in soft water with increased incidence of cardiovascular disease. These theories will be used to evaluate the health impacts of water treatment techniques.

The type of water treatment techniques implemented and their effects on the health of the public are dependent on the characteristics of the raw water. Section 4.4 will present a detailed description of the various treatment mechanisms and the conditions for effective hardening. The health effects from pH adjustment (with either lime or soda ash) and the use of corrosion inhibitors (either bimetallic polyphosphates or sodium silicate) are discussed below. Table 3-4 summarizes the water treatment mechanisms, presenting their various health and water quality issues.

TABLE 3-3

CHANGE IN DEATH RATE PER INCREASE IN WATER HARDNESS

Source of Data	Cause of Death	Change in Death Rate per Increase in Water Hardness 1/
Morris 2/	Cardiovascular Heart Disease	-0.65
Stitt 2/	Sudden Cardiac Death	-0.98
Crawford 2/	Sudden Cardiac Death	-0.98
EEA	Major Cardiovascular Diseases (390-448) 4/	-1.02 2/ .63 3/

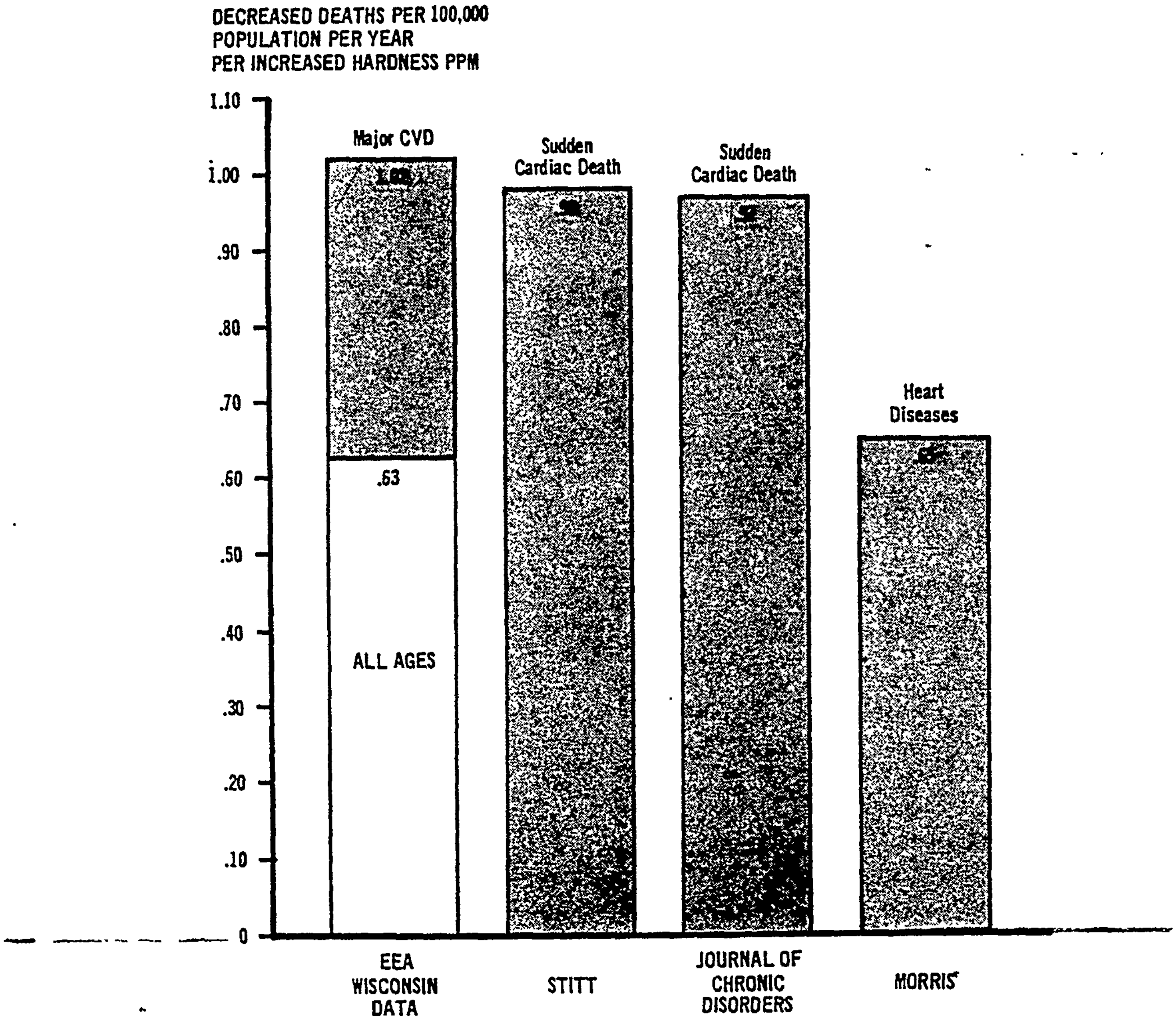
1/ Deaths per 100,000 exposed population per year per ppm increase in hardness.

2/ Exposed population and rate in men ages 45-64.

3/ Death rate is from U.S. census, water data as noted previously.

4/ Numbers refer to death categories as specified in International Classification of Diseases, 8th Revision.

FIGURE 3–7
EXCESS DEATHS OF MALES BETWEEN THE AGES OF 45–64 DUE TO SOFT WATER
— SELECTED STUDIES —



SUMMARY TABLE 3-4

Water Treatment Mechanisms				Health Benefits	
Water Treatment Method	Treatment Mechanisms	Problems/Comments	Effect on Water Quality	Class 1 1/ 2/	Class 3 3/
pH Adjustment-Lime Addition.	Increase pH using lime, water becomes less corrosive.	Most effective in waters with low hardness and low pH. Adequate carbonate levels are required.	Possible increase in trihalomethane formation, a suspected carcinogen; 30% decrease in chlorine effectiveness.	Calcium and magnesium levels increase.	Reduce cadmium and lead leaching.
pH Adjustment-Sodium Hydroxide or Soda-Ash Addition.	Increase pH using Sodium Hydroxide or Soda-Ash, water becomes less corrosive.	Most effective in waters with low pH and adequate calcium levels. Extremely expensive.	Possible increase in trihalomethane formation; 30% decrease in chlorine effectiveness; slight increase in sodium, which is related to hypertension.	No effect: will not increase calcium or magnesium levels.	Reduce cadmium and lead leaching.
pH Adjustment-Lime and Soda-Ash Addition.	Increase pH using Lime and Soda Ash, water becomes less corrosive.	Most effective in waters with low hardness and low pH.	Possible increase in trihalomethane formation; 30% decrease in chlorine effectiveness; slight increase in sodium.	Calcium and magnesium levels increased.	Reduce cadmium and lead leaching.
Corrosion Inhibitor-Addition of Silicates.	Formation of a protective film on pipe surfaces, which reduces corrosion.	Increased potential for deeper pits in galvanized and steel pipes.	No adverse effect; slight increase in sodium levels if sodium silicate is used.	No effect; will not increase calcium or magnesium levels.	Reduce cadmium and lead leaching.
Corrosion Inhibitor-Addition of Polyphosphates.	Formation of a protective film on pipe surfaces, which reduces corrosion.	Increased potential for algal growth in storage reservoirs and receiving bodies.	May have adverse effect on taste and odor of treated water.	Calcium levels increase. Magnesium levels will not be affected by treatment.	Reduce cadmium and lead leaching.

1/ Class 1: One or more of the major components of hard water (calcium and/or magnesium) that are present in lower amounts in soft water are protective.

2/ Class 2: Assumption not documented due to lack of supporting evidence.

3/ Class 3: One or more of the components in soft water are harmful--this includes metal ions leached from the distribution system (Cadmium, Copper, Lead, Beryllium).

3.5.2 Health Effects

Use of lime addition as a treatment process can have several beneficial health effects due to the associated increases in calcium, magnesium and pH levels following treatment. Since both magnesium and calcium are hypothesized to have protective roles with respect to CVD, decreased CVD incidence may result. The increased pH combined with the effects of stabilization will reduce the corrosion potential and hence reduce cadmium and lead leaching. A reduction in these elements, which are associated with an increased risk of CVD, would again be beneficial to public health. One adverse health impact due to the increased pH associated with lime addition is the potential formation of trihalomethanes, a reaction which is pH sensitive. The Seattle corrosion study found that, under worst case assumptions, the concentration of trihalomethanes formed as a result of pH adjustment was lower than EPA's proposed limit for trihalomethanes. At worst, only a very slight health risk may be associated with trihalomethane generation.

Addition of soda-ash (sodium bicarbonate) or sodium hydroxide may result in decreased CVD risk due to the decreased corrosivity and hence decreased cadmium and lead leaching. Neither calcium nor magnesium levels are increased. As with other upward adjustments of pH, a slight risk due to trihalomethane generation may be present from these treatments. Increased sodium intake associated with these treatments will occur, However, since sodium intake will increase 8 mg per person per day and natural intake is 1900-9600 mg per day, this will not present a significant impact. Even for people on restricted sodium diets, this level will not be burdensome. The increased bicarbonate intake associated with soda-ash addition would represent only 0.1 percent of the amount present in the blood and will not create adverse health impacts.

Another method of pH adjustment is the combined addition of lime and soda ash. Obviously, this addition will result in benefits similar to those described above for the separate treatments. An additional method using polyphosphates or silicates decreases corrosiveness without increasing hardness. This may lead to lower CVD by decreased leaching of toxic metals such as cadmium from the water distribution sytem.

3.6 POPULATION EXPOSED TO SOFT WATER

Soft water is defined as water having less than 60 parts per million of hardness expressed as equivalents of calcium carbonate ($CaCO_3$). Calcium and magnesium concentrations comprise the majority (almost 99 percent) of the hardness measurement, while aluminum, iron, manganese, strontium and zinc make up the remainder.

To prevent excess scaling, many utilities soften hard water, but none of the available softening techniques used by the utilities reduce hardness to less than 60 ppm (as $CaCO_3$). Therefore, all hard water areas will be assumed to deliver hard water at the tap even though the hardness may be somewhat less than that of the untreated water.

It is assumed that there is no change in water quality due to transportation from the source to the tap. Areas with raw soft water supply will be assumed to deliver soft water at the tap. One should note, however, that there are several documented studies indicating that the hardness of water flowing through cement-based pipes will increase from the leaching. However, for the purposes of this report, we assume that this will have little effect on the large population exposed to soft water.

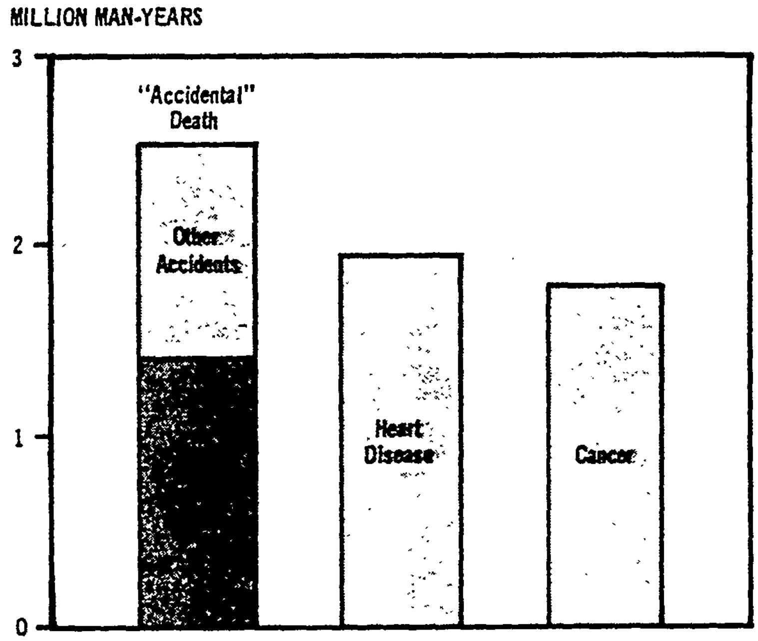
Soft groundwater areas were identified in a Water Information Center publication and soft surface water areas were identified in a National Stream Quality (NASQAN) publication. Areas which had both soft ground and surface waters were characterized as being exposed to soft water. For areas having either soft ground or surface water but not both, state by state breakdowns for origins (ground or surface water) were used to determine the population exposed to the soft water source. Unfortunately, county breakdowns by supply source were not obtainable. A regional disaggregation of soft water areas is listed in Table 1-3 and portrayed in Figure 1-1. Regions with substantial incidence of soft water are the New England, Mid-Atlantic, Southeastern and Northwestern areas of the United States. A more detailed explanation of the methodology is presented in Appendix A.

Approximately 27 percent of the United States population was exposed to soft water in 1970. This amounts to a population of roughly 55.3 million. The eastern states contain about 55 percent of the total population exposed to soft water. Many of these states are totally dependent on soft drinking water, including Delaware, Maine, Maryland, Massachusetts, New Hampshire and Rhode Island. Soft water areas in the southern states amount to approximately 38 percent of the soft water population. States which are greater than 90 percent dependent on soft water are Mississippi and North Carolina. A very small percentage (7%) of the soft water population was located in the western region. Hawaii is the only state in the western region, which is totally exposed to soft drinking water.

Expanding this data to encompass corrosion indices, the Midwest Research Institute survey of all water utilities serving populations more than 50,000 indicated that about 70% of the populations studied is exposed to water which ha a negative Langlier Saturation Index (LSI) when it enters the distribution system. This means the water is at least mildly aggressive. About 30% of the population (32.3 - 36.5 million) is exposed to water with an LSI below -1.0 before distribution; about 10% (11.3 - 13.4 million) drink water that has an LSI less than -2.0 when it enters the distribution system. This water can be considered highly aggressive.

FIGURE 3–8

1975 LOSS OF WORKING LIFE – ANNUAL MAN-YEARS*



*Loss of working life is defined as the working years between the ages of 18 and 65 that are lost due to death before age 65.

3.7 Health Cost Related to CVD

Heart disease is the number one killer in the United States, accounting for 37.8 percent of total deaths in 1975. It is second only to accidental deaths in terms of man-years lost, based on working years in the 18-65 year age range (see Figure 3-8). Accidental death exceeds heart disease in terms of man-years lost because accidental death victims are predominantly younger than heart disease victims.

The costs of heart disease are substantial. They include quantifiable costs (medical care, lost income, etc.) and unquantifiable costs (pain, lifestyle restriction, suffering, anxiety, family disruption). There is no accepted method for calculating these latter costs. One attempt to breakdown the quantifiable costs yields three categories:

- Direct Costs which measure physicians services, hospital services, drug expense, and other costs related to prevention, detection and treatment of heart disease.
- Morbidity Costs which reflect the loss of productivity due to illness.
- Mortality Costs which reflect the expected lifetime earnings of an individual had that person not died of CVD, but had lived an average lifespan.

Table 3-5 presents the estimated costs, as categorized above, of heart disease in the United States for 1975. Within the last decade and a half direct costs for heart disease have increased five-fold and morbidity costs have tripled, reflecting inflation and increased medical services rather than an increased number of victims.

If soft drinking water accounts for 2.8 percent of the total mortality rate as shown in Section 3.8, or 5.5 percent of the CVD death rate, the total health costs indicated by the above breakdown in the use of soft water in the United States is: 0.055 x $51.3 billion = $2.8 billion per year.

TABLE 3-5

ECONOMIC COST OF CARDIOVASCULAR DISEASE
IN THE UNITED STATES (1975)

Category	Cost ($Billion)	Percent of Total Cost
Direct Costs	16.1	31.5
Hospitalization	7.8	
Physician Services	2.8	
Nursing Home	3.7	
Drugs/Medications	1.8	
Morbidity Costs	8.8	17.0
Currently Employed	1.9	
Keeping House	0.6	
Unable to Work	5.4	
Institutionalized	0.9	
Mortality Costs	26.4	51.5
TOTAL	51.3	

Another way to estimate the health costs is life value estimation. The measure used for the value of a death from heart disease was the loss of the deceased's remaining earning potential. The value of life calculated in this manner was $255,800. This is the undiscounted expected value of lost wages in 1975 dollars. It was estimated by summation of the probability of death for the general population in nine age classes times the average wages in 1975 for each class. Algebraically, the expected value was estimated by:

$$EV\ (death) = \sum_{i=1}^{9} Pi\ [5\sum_{i=j}^{9} Y_j - 2.5Yi]$$

where i = an index referring to age group of the deceased

j = an index referring to age groups through which the deceased would have passed had he not died

P_i = probability of a randomly selected death from heart disease being a person from age group i

Y_j = average annual earnings for a person in age group j

Probability of death from heart disease by age class was obtained from the National Institute of Health. Consumer income data were obtained from the U.S. Department of Commerce. The value calculated in this fashion has a slightly low bias. It implicitly assumes that the average person who dies of heart disease earns the average amount for his age group. This is not strictly true. On the average, men are more likely to die from heart disease and also are more likely to earn more. Recognizing this limitation, it should be noted that the life value estimation approach yields a health cost figure that agrees well (within 20 percent) with that obtained using the cost breakdown method (see Section 3.8).

3.8 BENEFIT/COST OF CONTROLLING SOFT WATER

As discussed in earlier sections, increasing the hardness of the water before distribution in soft water areas, may reduce the mortality rate.

One issue which arises is how much of an increase is technically possible and/or practical. Soft water areas (less than 60 ppm as $CaCO_3$) have concentrations of calcium ions far below the saturation level. The American Water Works Association (AWWA) has estimated that for most water supply systems, the calcium carbonate saturation point lies between 80 and 100 ppm $CaCO_3$. To reach this optimal point would require that most soft water communities increase the hardness of their water supply by at least 40 ppm.

As determined in Section 3.4, a mortality rate from exposure to soft water was 0.63 lives per 100,000 population per part per million of $CaCO_3$. The mortality rate reduction that could potentially be gained by hardening soft water 40 ppm (as $CaCO_3$) equals 25 deaths per 100,000 population as shown below:

$$40 \text{ ppm } CaCO_3 \times \frac{0.63 \text{ lives/100,000 population}}{\text{ppm } CaCO_3} = \frac{25 \text{ lives}}{100{,}000 \text{ population.}}$$

<u>The United States Statistical Abstract</u> determined the mortality rate to be 889 deaths per 100,000 population. The percentage of the mortality rate attributed to the incidence of CVD from the exposure to soft water amounts to 2.8 percent.

$$\frac{25}{889} = 2.8\% \text{ of average death rate in soft water areas}$$

The actual mortality rate can be determined given the number of deaths that are attributed to being exposed to soft water and the population exposed to soft water. This amounts to a mortality rate of 13,800 lives per year as shown below:

$$\frac{250 \text{ lives saved}}{1 \text{ million pop.}} \times 55.3 \text{ million} = \frac{13{,}800 \text{ lives}}{\text{year}}$$

In Section 3.7, it was determined that a life was valued at $255,800. This would amount to an annual savings of $3.5 billion due to the lower incidence of CVD as shown below:

$$\frac{13{,}800 \text{ lives saved}}{\text{year}} \times \frac{\$255{,}800}{\text{life}} = \$3.5 \text{ billion/year}$$

A benefit-cost analysis can be determined from the 3.5 billion dollars that can be saved annualy from the exposure to soft water as opposed to the cost of hardening the water. Lime addition as determined in Section 4.4 has both cost and health benefits when used to control corrosion. The benefit-cost ratio is 300:1 and a corrosion control program implementing lime addition as a means to hard water is very favorable.

Treatment with lime addition.

Benefit = Reduced mortality rate.

Cost = Cost of corrosion control ($\$.21 \times 5.53 \times 10^7$).

$$B/C = \frac{3.5 \times 10^9}{1.16 \times 10^7} \cong 300$$

4. CORROSION IN AGGRESSIVE WATERS

4.1 CORROSION IN WATER DISTRIBUTION SYSTEMS

Corrosion of water distribution pipes is attributable to three mechanisms--physical abrasion, electrochemical reactions, and dissolution. Physical abrasion is dependent upon the suspended solids concentration and water velocity. It occurs when suspended solids strike the pipe walls at high velocities and erodes the pipe. This type of corrosion increases with increasing suspended solids concentration and flow velocity. Since the suspended solids are greatly reduced by water treatment prior to distribution, physical abrasion is not the predominant type of corrosion. However, in pipe segments which have either deteriorated with age or broken by improper loading, sand and grit can be introduced into the system which will increase physical abrasion significantly.

The most common corrosion mechanism in water supply systems is electrochemical. This type of corrosion results from the flow of an electrical current from the anodic to the cathodic areas on the pipe surface. At the anode, oxidation reactions occur which release electrons to the cathode and the divalent metal ion into the water. At the cathode, reduction occurs. The rate at which electrochemical corrosion occur is dependent upon a number of factors including:

- temperature;
- dissolved oxygen;
- pH;
- alkalinity; and
- hardness.

As the temperature of the water increases, the electrochemical corrosion rate also increases. More energy becomes available for chemical reactions as the temperature increases, thereby increasing the potential for a reaction to occur. However, in water distribution systems, temperature is one parameter that cannot be controlled.

Dissolved oxygen (DO) is needed for the oxidation reactions at the anode. By lowering the DO available, the overall corrosion rate can be decreased. Current water treatment techniques are not designed to reduce the level to a point low enough to effect corrosion rates.

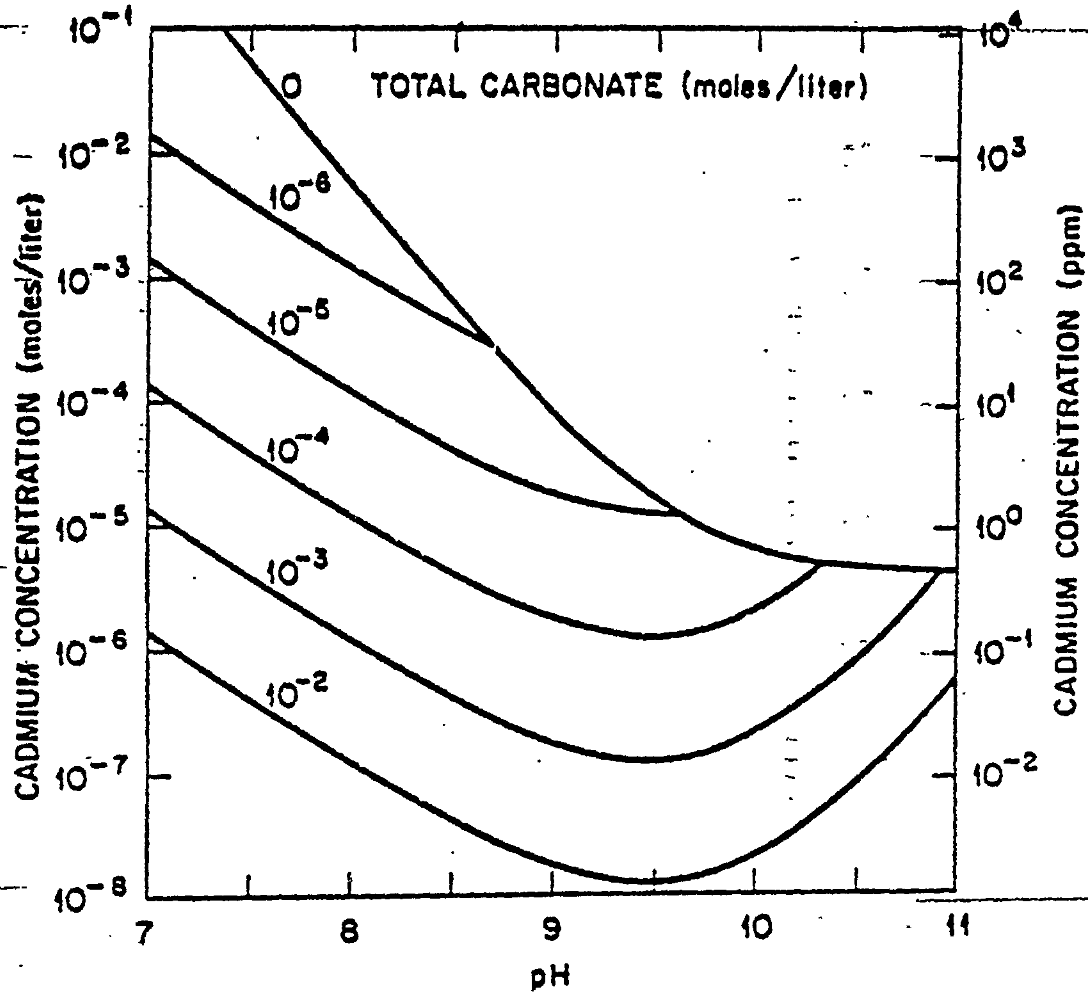
The pH, alkalinity, and hardness levels can be controlled to lower corrosion rates in the water distribution system. The hydrogen ion is essential in the reduction reactions at the cathodic areas. By raising the pH of the water, the availability of the ion for these reactions is decreased and the reduction reactions are slowed considerably.

Alkalinity (a measure of $HCO_3^-/CO_3^=$ ions) has long been recognized as an essential factor in controlling corrosion. The carbonate and bicarbonate ions are involved in many electrochemical reactions. The metal cation reacts with the carbonate to form an insoluble carbonate salt film. This film not only limits the solubility of the metal but also protects it from further corrosion. Since solubility is a measure of the tendency of a metal ion to go into solution, it can be used to estimate the corrosion potential. Figures 4-1 and 4-2 show the solubility of lead and cadmium as it varies with pH and alkalinity. The greater the alkalinity the lower the solubility and corrosion potential. As shown in Figure 4-3, the corrosion rate of mild steel increases with decreasing alkalinity.

Hardness is an indicator of the concentrations of calcium and magnesium. These cations play an important role in the formation of insoluble salts

FIGURE 4-1

The Solubility of Cadmium vs pH and vs Total Carbonate Concentration

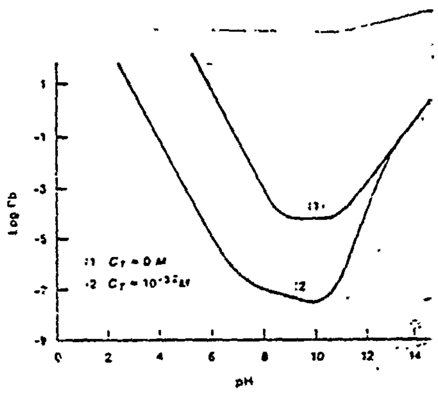


The Solubility of Cadmium vs pH and vs Total Carbonate Concentration. For zero carbonate, the solid is cadmium hydroxide [$Cd(OH)_2$]. For the other curves it is cadmium carbonate ($CdCO_3$).

SOURCE: W. Fulkerson, et. al., "Cadmium The Dissipated Element."

FIGURE 4-2

LEAD SOLUBILITY AS A FUNCTION OF pH



Line 1 represents lead hydroxide solubility at zero carbonate.
Line 2 represents solubility at $10^{-3.2}$ molar carbonate.

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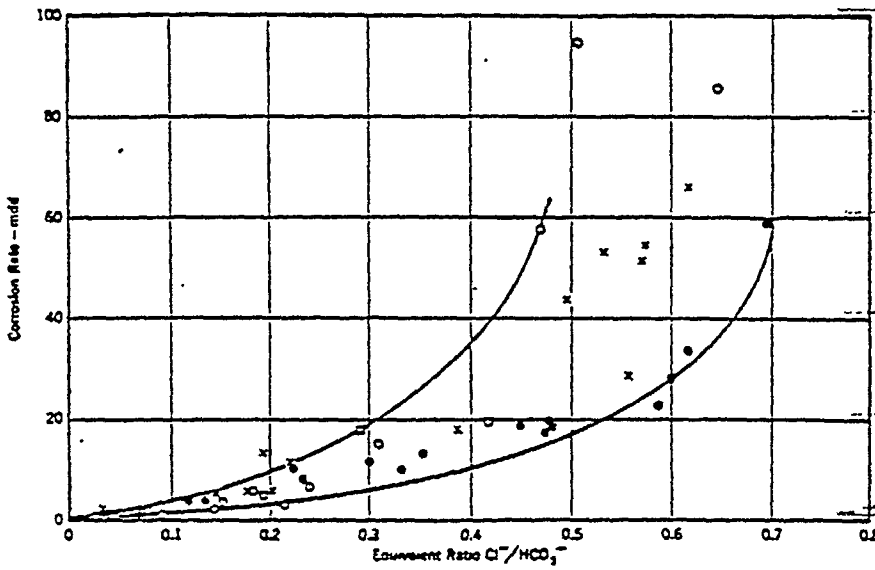
FIGURE 4-3

THE SOLUBILITY OF MILD STEEL V.S.
CHANGE IN ALKALINITY



Alkalinity (as $CaCO_3$) is shown as follows:
●— 75–100 ppm, ○—150–180 ppm,
×—120–135 ppm, □—250–260 ppm.
The abbreviation "mdd" stands for milligrams per square decimeter per day.

with high adherence on the pipe walls. This film, once formed, halts the oxidation reactions at the anode by stopping the flow of oxygen to the corrosion "cell." Often this deposition of protective film will occur only when the cations reach a saturation point in solution. Although this point is a function of the pH, CO_2 level, and temperature, among others, it roughly occurs at a hardness level between 80 to 100 ppm. By increasing the hardness in soft water areas (assuming a sufficient alkalinity is also present), the corrosion rates can be decreased significantly.

Dissolution reactions, such as those which occur with cementitious pipe products, are not electrochemical in nature. Rather, the process is one in which low pH and/or hardness water leach calcium and magnesium from the cement and, in doing so, corrode and reduce the structural integrity of the conduit.

Corrosion rates due to dissolution can be decreased by increasing the hardness, in conjunction with the pH or alkalinity of the conveyed water. Currently, there is insufficient data to elucidate which of these three factors is most important in the dissolution reaction. However, due to the high calcium and magnesium content of cement, it must be presumed that water hardness is a major factor involved.

Three indices have been develop to estimate the corrosion potential of water. These include the Langlier Saturation Index (LSI), the Aggressiveness Index (AI), and the Ryznar Stability Index (RSI). All of the indices measure the same parameters including calcium (may be expressed as calcium hardness as $CaCO_3$), alkalinity (expressed in mg/liter as $CaCO_3$), and the pH of the water. The indices are defined as the difference between the pH measured of the water and the pH at which $CaCO_3$ would be at the saturation point.

The Langlier Saturation Index is widely used and can be applied to those waters with a pH between 6.5 to 9.5. L.S.I. may be defined as:

LSI = pH measured -pH saturation
which is equivalent to:

$$LSI = pH_{measured} + \log [(Ca^{++})(Alkalinity)] - C$$

where $C = 9.3 + \log (\frac{Ks}{K_2}) + \frac{2.5 \sqrt{\mu}}{1 + 5.3 \sqrt{\mu} = 5.5}$ $\cong 12$ for typical temperatures and solids found in water supplies

K_s = solubility constant for $CaCO_3$
K_2 = second ionization constant for H_2CO_3
(Ca^{++}) = calcium ion concentration in mg/l
(Alk) = alkalinity in mg/l as $CaCO_3$

The pH limit may restrict the usage of the L.S.I. in waters with a lower pH, potentially including soft, corrosive water. Positive LSI values indicate a tendency for the water to deposit a protective $CaCO_3$ film on the pipe, and therefore reduce corrosion. Negative LSI values suggest the tendency to dissolve the $CaCO_3$ film from the pipes' interior surfaces and thus increase the potential for aggressive (corrosive) conditions. The constant values in the equation are the temperature and total dissolved solids content of the measured water.

The Aggressiveness Index (AI) is obtained by subtracting the constant from the L.S.I. expression.

$$AI = pH \text{ measured} + \log (AH)$$

where A = alkalinity in mg/liter as $CaCO_3$
H = calcium hardness in mg/liter as $CaCO_3$

This equation is a simplified version of the Langlier Index and specifically includes calcium hardness as a parameter. The inclusion of a hardness factor in the AI is an important consideration when determining a corrosion regulation to protect public health. This is because calcium and magnesium are known protective elements.

The aggressiveness of a water may be separated into three categories. A nonaggressive water would have an AI greater than 12.0, moderately aggressive water are between 10 and 12 and highly aggressive waters have an AI of less than 10.0.

The Ryznar Saturation Index (RSI) uses the same parameters as the LSI and AI, although it puts more emphasis on the effect of pH, and not just the difference between the pH measured and the pH saturation. The RSI is defined as:

$$RSI = 2pH\ saturation - pH\ measured$$

A corrosive water has values of above 7.0 while those below that value indicate scale-forming tendencies. The RSI may be the most effective method of regulating soft, corrosive water as it can be applied to waters of different compositions. This index is not pH restrictive as both the LSI and AI are, and can therefore be applied to pH's lower than 6.5.

Each of the above corrosion indices was developed to address certain conditions found in water supply. However, for the vast majority of water supply systems, any of the three indices could be used to calculate the stability of water. By stabilizing the water using any one of the indices, a utility can be confident that the resulting water would be non-aggressive.

4.2 SUMMARY OF PAST STUDIES ON CORROSION

Chemical changes occur in water throughout the distribution system and can be related to corrosion found in pipes. As treated water leaves the plant and enters the distribution system, it is subject to interaction with various other water elements and with the distribution system. Associated with water hardness are calcium and magnesium salts, which are excellent coprecipitators of divalent ions such as zinc, cadmium, and lead. These elements often adhere and accumulate on the walls of the pipes in the distribution system.

Many different trace metals can occur in drinking water. They may occur naturally, from chemical treatment of the water, or may be from the corrosion of the distribution system and household plumbing.

McCabe, in 1974, conducted a survey in Chicago to determine the metal content found in various areas of a single distribution system. In order to give an indication of metal corrosion and variability, composite samples were collected at treatment plants and these results were compared with 550 grab samples collected from the distribution system. The metals resulting from pipe corrosion (and with percentage of each sample showing an increase) were: cadmium (15), chromium (17), cobolt (10), copper (28), iron (39), lead (20), manganese (32), nickel (34), silver (15), and zinc (67).

Distribution studies were conducted by Dangel in 1975 to illustrate the effect of soft water on tap water in Seattle, Washington. The water used in Seattle is impounded surface water and is treated by chlorination and fluoridation, with fluorosilicic acid (H_2SiF_6). The pH is slightly acidic and the hardness and alkalinity of these waters are extremely low. Also, dissolved oxygen in Seattle's water also approaches the saturation point. The distributed waters exhibit aggressive corrosion tendencies and are excellent solvents. Table 4-1 displays the water quality parameters that were measured at the source of the treated water.

Metal pickup is related to the type of plumbing material used. In Seattle, copper and galvanized iron were commonly utilized, and, as indicated in Table 4-2, there were noted increases in copper and iron concentrations. The increase in lead can be related to the solder used to join the copper piping.

Craun and McCabe, in 1976, studied the water distribution system in Boston to determine corrosiveness of the conveyed water. Chlorination was the only method of treatment for raw water in Boston. It was found that low hardness and alkalinity were common within this water system and the water was characterized by low pH. The waters exhibit aggressive corrosion tendencies and are excellent solvents. Therefore, a comparison can be made between similar water characteristics in Boston and Seattle distribution systems and different materials used. In Boston, a high percentage of sampled households have lead service pipes. As is displayed in Table 4-2, there were 65 percent of the homes sampled which exceeded EPA drinking water standards for lead.

Corrosion can be localized in the water distribution system. Although some studies have not detected this variable, studies in the Northeast have shown that milligram per liter levels of lead can be found in some areas of a distribution system while in other areas of the same system only negligible amounts may be detected (Karalekas, 1977). Such was the case for a single distribution system in New York. McCabe conducted a random sample survey in New York City and found that 3 of 77 samples (4 percent) analyzed had the maximum contaminant level (MCL) of 0.05 mg/l lead. However, in a similar study conducted by DeZuane, tabulation of available records showed that 77 of the 690 samples (11 percent) analyzed exceeded the MCL. This obvious discrepancy can be attributed to the local occurrence of lead in the distribution systems.

TABLE 4-1

WATER QUALITY PARAMETERS MEASURED IN TREATED WATER AT THE SOURCE

Parameters	Seattle	Boston (MDC)
pH	5.5	6.7
Hardness (as $CaCO_3$)	6.0ppm	14.0ppm
Total Dissolved Solids (TDS)	No data	50.0ppm
Alkalinity (as $CaCO_3$)	2.0ppm	8.0ppm
Chlorides	1.7ppm	12.0ppm
Calcium	2.1ppm	No data
Magnesium	0.3ppm	No data
conductivity	20 umbo	No data

*MDC = Mean Daily Concentration

Source: Craun, G.F. and L.J. McCabe, 1976. Review of the Causes of Waterborne-Disease Outbreaks. J.M. Water Work Association 65:74. Dangel, R.A. 1975. Study of Corrosion Products in the Seattle Water Department Tolt Distribution System. EPA Report 670/2-75-036. U.S. EPA, National Environmental Research Center, Cincinnati, 22 pp.

TABLE 4-2

PERCENTAGE OF HOMES WITH A SAMPLE EXCEEDING
EPA DRINKING WATER STANDARDS

Metal	Seattle	Boston
Cadmium	7	0
Chronium	No data	0
Copper	24	19
Iron	76	9
Lead	24	65
Manganese	5	No data
Zinc	10	0

Source: Dangel 1975, Craun and McCabe 1976.

A thorough investigation is needed in order to determine the extent to which corrosivity can vary within a single distribution system. There are a number of known variables such as the age of the distribution system, the type of pipe used, raw water quality and methods of corrosion control.

4.3 EFFECTS OF CORROSION

4.3.1 Potential Health Risks from Corrosion Products

Seven metals have been reported to leach from water distribution lines as a result of corrosion. These include cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), lead (Pb), manganese (Mn), and zinc (Zn). Health effects are listed below for each element.

- Cadmium-Cadmium given to rats produces hypertension. Long-term low level exposure (5 ppm) also produces adverse cardiac effects that are evidenced as abnormal electrocardiograms. Acute exposure to cadmium produces acute gastrointestinal distress and vomiting in humans. Chronic cadmium poisoning produces a severe environmental disease referred to as "Itai-itai" in Japan. Itai-itai is characterized by leg pain, kidney damage, skeletal deformities, and calcium loss leading to facile bone fracturing. A level of 5 ppm cadmium given to rats or mice in drinking water results in high tumor incidence, shortened life-span, cirrhoses of the liver, and organ damage in addition to hypertension.

- Chromium-Chromium may yield some protection from cardiovascular disease. Two valence states, trivalent and hexavalent, are predominant in biological systems. Hexavalent chromium is considered to be toxic to mammals, whereas the trivalent form is an essential trace element. Chromium deficiency resembles diabetes in terms of symptoms, and is also known to produce aortic plagues in rats. Interestingly, a deficiency of trivalent chromium also increases the toxicity of lead. The concentration of chromium in natural water supplies is generally less than 10ppb, although concentrations up to 35ppb have been reported in some municipal water supplies.

- Copper-May be positively correlated with cardiovascular mortality. Copper can be quite toxic. One infant death is reported due to consumption for 14 months of drinking water that contained 6.75mg/liter copper. One adult death has been reported involving ingestion of 1.0g of copper sulfate. High copper intake may be related to Wilson's Disease, which involves brain and liver damage. Although copper is an essential element for man and animals, the concentration range separating deficiency effects and toxicity effects is small. Copper is also a gastrointestinal irritant. Acute poisoning has symptoms ranging from vomiting to coma and death.

- Iron-Excess dietary iron intake has been related to increased cardiovascular disease in native South Africans. Iron is an essential element that has a complex transferrin-ferritin transfer and storage system in the body. Iron is involved in both enzymatic and oxygen transport functions. Acute toxicity from oral iron supplements has been experienced and is manifested as gastrointestinal tract irritation, vomiting, bleeding, and lethargy, jaundice, pnenmonitis, and convulsions.

- Lead-Lead may be related to increased incidence of heart disease. A study of heart tissues of myocardial infarct victims in soft and hard water areas show about 5 times the level of lead in the hearts of those from the soft water area compared to the hard water area. Chronic lead exposure can lead to many symptions, the most severe of which is CNS effects, including encephalopathy and intellectual deterioration. Very young children and those with zinc deficiencies form two high risks groups for the toxic effects of lead. Acute lead poisining is rare, but when it occurs it can involve nausea, vomiting, and circulatory collapse.

- Manganese-Manganese may have a protective effect on the cardiovascular system. Manganese is an nutritionally essential trace metal which is present in the majority of U.S. water supplies in a concentration range of 1-3250 mg/l. Ingested manganese is low in toxicity, although it can cause gastrointestinal irritation. However, one incident of intake of large amounts caused an encephalitis-like illness characterized by high muscle tone, rigidity, and tremors. Manganese deficiency produces a diabetes-like syndrome in guinea pigs, suggesting an involvement in pancreatic function.

- Zinc-Zinc has a very weak correlation with cardiovascular mortality. Zinc toxicity in man is rare. Rather, a nutritional deficiency of zinc may be a problem for a large segment of the population. Occasionally accidental oral toxicity does occur and is noted by a combination of fever, vomiting, cramps, and diarrhea in a way which resembles gastroenteritis. Tumors have been produced by intratesticular injection of zinc salts in rats and chickens, although other routes have not produced carcinogenic effects in animals.

In addition, asbestos fibers may become disassociated from asbestos cement pipe in the presence of corrosive water. Asbestos is a naturally-occurring fibrous silicate mineral that occurs under various geological conditions. Chronic inhalation of asbestos fibers can result in asbestosis. This disease is characterized by thickening and calcification of the lining of the lung, leading to reduced respiratory capacity. Clinical symptoms may not develop until after 10 to 20 years of occupational exposure. Bronchial cancer is also associated wth inhalation of asbestos fibers, the disease appearing 20 to 30 years after the beginning of the chronic exposure period. This has been observed in both experimental animal studies and in epidemiological studies. Mesothelioma, a rare and rapidly fatal malignant disease, also occurs at a higher than usual incidence rate in asbestos workers.

There has been some concern expressed by the scientific community and by the public that ingested asbestos fibers may cause gastrointestinal cancer in man. This is supported by epidemiological evidence indicating an increased incidence of gastrointestinal cancer in asbestos-exposed workers. However, this conclusion is countered by the fact that it has been difficult to induce gastrointestinal or asbestos-related cancer in laboratory animals with asbestos.

4.3.2 Water Loss Costs Related to Corrosivity

Water loss occurs from leakage and breakage of the distribution and residential plumbing pipes. The loss of water from the corrosive effects of aggressive water can be substantial. However, it is difficult to discern those costs which are directly the result of corrosion and those costs which are the result of natural and deterioration. Water loss constitutes to an economic loss to the utilities and the consumer.

It has been estimated by the National Science Foundation that nationally 15 percent of the water distributed is lost. The EPA has determined that as much as 50 percent of the water leaving a treatment plant may be lost before ever reaching the consumer. This analysis will use the national average of 15 percent as a conservative estimate of water loss. It should be noted that of this 15 percent not all of the water loss is due to aggressive water. From data collected from a utility survey (MRI), an estimate of the water loss due to corrosion exclusive of natural deterioration was calculated. The data attributed approximately 38 percent of all water loss or 6 percent of the total water distribution volume to corrosion from aggressive waters (see Figure 4-4).

A rough estimate of the costs can be made by assuming operating costs of pumping facilities to be proportional to the total flow. Assuming approximately a 15 percent water loss average of which 38 percent can be attributed to corrosive water, operating costs of 20¢ per 1,000 gallons, and average residential use of 100 gallons per capita per day, water loss due to corrosion related leakage is estimated at $0.42 per capita annually. It should be noted that the impacts from increased hydraulic flow resistance from corrosion are omitted in this calculation. Water loss damage due to corrosion can be partially eliminated and the costs reduced if a water treatment program is implemented to increase hardness in aggressive soft water.

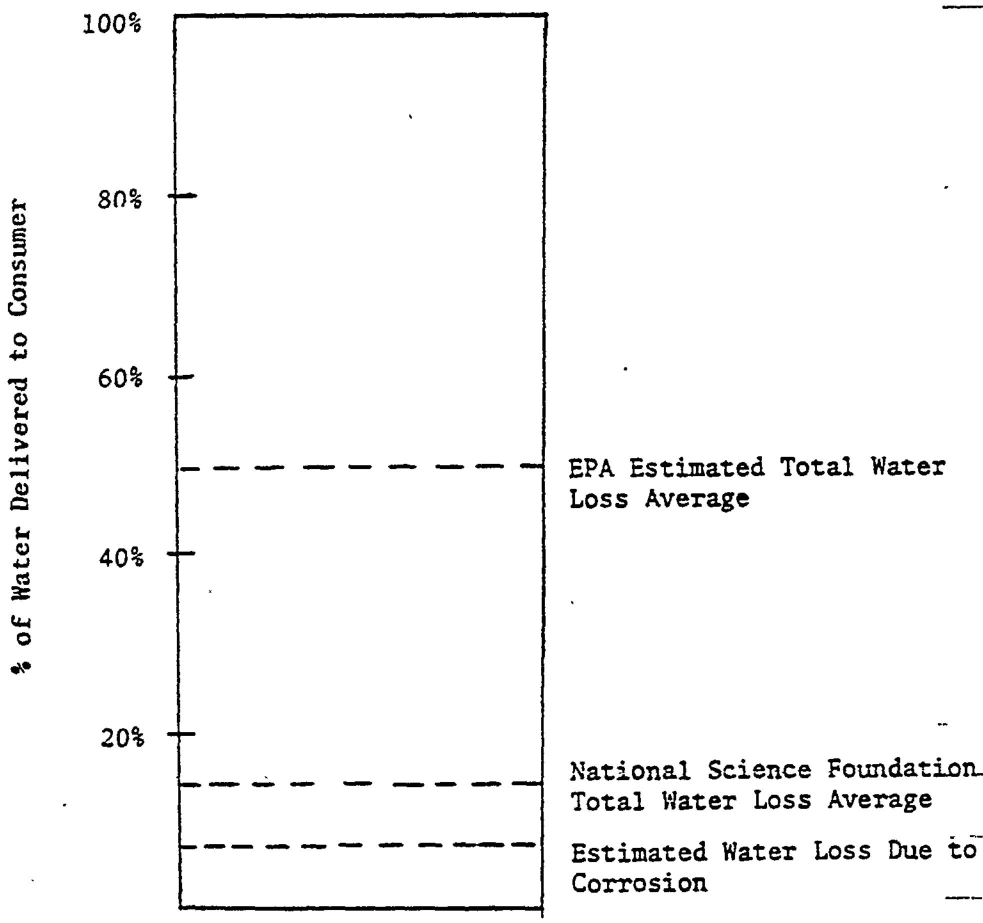
4.3.3 Economic Impacts of Corrosion

Introduction

Economic impacts from conveyance of aggressive water can be disaggregated into two components: repair of corrosion-related degradation and costs associated with public health and esthetic impacts. The following section evaulates the economic impacts of corrosion from aggressive waters in terms of distribution network repair, pipe replacement, and

FIGURE 4-4

PERCENTAGE OF WATER LOSS



increased pumping requirements. Costs associated with adverse health and esthetic effects are discussed in Section 3.8.

As discussed in Section 4.1, the presence of soft or aggressive water in distribution systems increases the corrosion rate and, hence, is the repair and replacement of pipe and other appurtenances. Similar impacts occur in residential plumbing. Also, additional corrosion-related costs are incurred at the pumping facility since increased pumping pressures must be maintained to compensate for water loss from pipe leakage and decreased pipe diameter from heavy scaling and tubercular pipe corrosion. An important consideration is the distinction between natural deterioration due to water abrasiveness and that caused by corrosive water. Obviously, the economic impacts due to corrosion in a given community will be dependent upon a number of factors including the age of the distribution system, piping material, design and construction practices, and the extent of water corrosivity. An evaluation of economic losses from the action of aggressive water in distribution systems is presented below.

Economic Analysis of Corrosion

Most studies of water-related pipe corrosion fail to distinguish between the inherent abrasiveness of water and the increased corrosion due solely to aggressive water incidence. Generally, combined corrosion rates can be quantified directly; however, estimation of either corrosion due to abrasiveness or corrosion due to aggressive water can be difficult. Data from a national survey of utilities showed that corrosion-related repairs in utilities with non-aggressive water (a surrogate measure of corrosion due to natural abrasiveness) were approximately 62 percent of those in utilities with aggressive waters (LSI <-0.5). Thus, the average impact of corrosive waters was 38 percent of the total observed corrosion rate. Data from the Seattle corrosion study maintained that corrosion rates could be reduced from 30 to 75 percent, if treatment of corrosive water was implemented. Since corrosion control in no way affects natural abrasiveness, at least 30 to 75 percent of the total pipe deterioration can be attributed to the incidence of aggressive water. Since corrosion control treatments are not totally effective, these figures will underestimate the actual impact of water corrosivity in Seattle, and elsewhere. This study suggests that the impact of water corrosivity can exceed the abrasiveness inherent in water by greater than 400 percent. However, for the purposes of this study, impacts due to water corrosivity will be conservatively estimated at 38 percent of the total corrosion rate. This figure will be used to determine the economic impacts which are preventable with corrosion control treatment.

The primary economic features of corrosion in distribution networks or plumbing systems are pipe or equipment replacement or repair due to scaling, leakage, or breakage. Although degradation of meters and storage facilities can be economically significant, the dominant maintenance item is pipe replacement. Costs for replacement of water-related pipe corrosion in distribution systems with aggressive water can range up to $20.16 per capita annually, with an average of $1.19 per capita annually. When costs for natural deterioration are subtracted, costs for corrosion due only to aggressive water incidence average $0.45 per capita annually. Since costs for corrosion-related repair of meters and storage facilities are not included, this estimate must be considered conservative. Independent researchers have estimated total national costs due to pipe corrosion (including natural deterioration) at $375 million annually, which, although somewhat high, generally supports the above estimates.

Corrosion-related repair of residential plumbing may represent a much more substantial economic burden to the consumer than maintenance of distribution systems; however, few studies have quantified the residential impacts of soft water. Residential plumbing is particularly susceptible to corrosion due to the small diameter pipe utilized. The higher ambient temperatures of residential dwellings, especially in hot water plumbing, also accelerate the corrosion rate. The Seattle study estimated that the annual cost of corrosion-related maintenance for residential plumbing alone was $6.6 million or approximately $7.00 per capita annually. Approximately $2.0 million could be saved annually if corrosion control treatments were implemented. Only $0.445 million was necessary to repair corrosion of transmission and distribution systems. Thus, in that study, maintenance of residential plumbing was approximately fifteen times as costly as maintenance of distribution mains.

Unfortunately, no national estimates of corrosion-related repair of residential plumbing exist nor is there any evidence to suggest that Seattle's figures are unusually high or low. However assuming that corrosion costs will be proportional to overall pipe length, an estimate can be made of residential plumbing corrosion costs given data from maintenance of distribution systems. Since approximately four times as much pipe is used in residential plumbing systems as in distribution systems (80 feet per capita versus 20 feet per capita), corrosion costs for residential plumbing will be approximately four times higher than costs of distribution network maintenance or $1.80 per capita annually. This estimate neglects the increased corrosion rate associated with residential plumbing and is more conservative than the Seattle estimate.

4.3.4 Conclusions

Pursuant to the above discussion, Table 4-3 summarizes the economics of pipe corrosion caused by aggressive water incidence. These costs exclude national deterioration due to water abrasiveness and represent the potential savings corrosion control treatments would generate. Total costs to the consumer are conservatively estimated at $2.67 per capita annually in areas with aggressive water. Obviously, the actual costs will vary considerably from these averages, dependant mainly on the corrosivity of the water and the susceptibility of the piping material.

4.4 CORROSION CONTROL TECHNOLOGIES

4.4.1 Introduction

Due to the significant impacts associated with corrosive water, it is desirable that water be stable, i.e. non-corrosive, as it leaves the treatment facility and enters the distribution system. Chemical control is the preferred method of controlling corrosivity and can be achieved by a number of methods, normally dependent upon characteristics of the water (refer to Table 4-4). Two categories of chemical control--pH adjustment and corrosion inhibitors--exist and will be described in some detail.

A survey by the U.S. EPA showed that utilization of corrosion controls ranged from 14 percent of all utilities in groundwater-supplied communities to 18 percent for surface water-supplied utilities (see Table 4-5). The slightly higher percentage for surface water-supplied communities is due to the fact that these communities are generally of high population density and, hence, utilize older, more deteriorated systems which have more need of corrosion control.

Currently, the utilization of corrosion controls is greater in large population centers. The EPA study determined that 68 percent of the utilities in cities with populations greater than 100,000 employed some type of corrosion control in their water distribution system. In urban areas with populations greater than a million, 91 percent used corrosion controls. Table 4-6 summarizes the precentage of systems that utilize corrosion control according to population category. One factor supportive of such a distribution is the direct relationship between distribution system size and age (see Table 4-7). Generally, large cities have extremely old systems, averaging over 90 years old. These older water distribution systems often utilized less corrosion-resistant material than are presently used or available, thus increasing the susceptibility

TABLE 4-3

COSTS OF CORROSION-RELATED

DEGRADATION OF PIPE AND PLUMBING*

Nature of Cost	Estimated Cost in $/capita/year	Comments
Distribution System Maintenance	0.45	Excludes storage facility and meter deterioration.
Residential Plumbing Maintenance	1.80	Assumes corrosion rate is equal to that in distribution system. Neglects higher corrosion rates due to small diameter plumbing and high ambient temperatures.
Pumping Facility Operation	0.42	Includes only costs due to water loss. Impacts from increased hydraulic flow resistance from corrosion are omitted.
TOTAL	2.67	

* excludes impacts of natural deterioration due to water abrasiveness.

SUMMARY TABLE 4-4

Water Treatment Mechanisms				Health Benefits	
Water Treatment Method	Treatment Mechanisms	Problems/Comments	Effect on Water Quality	Class 1/ 2/	Class 3/
pH Adjustment-Lime Addition.	Increase pH using lime, water becomes less corrosive.	Most effective in waters with low hardness and low pH. Adequate carbonate levels are required.	Possible increase in trihalomethane formation, a suspected carcinogen; 30% decrease in chlorine effectiveness.	Calcium and magnesium levels increase.	Reduce cadmium and lead leaching.
pH Adjustment-Sodium Hydroxide or Soda-Ash Addition.	Increase pH using Sodium Hydroxide or Soda-Ash, water becomes less corrosive.	Most effective in waters with low pH and adequate calcium levels. Extremely expensive.	Possible increase in trihalomethane formation; 30% decrease in chlorine effectiveness; slight increase in sodium, which is related to hypertension.	No effect: will not increase calcium or magnesium levels.	Reduce cadmium and lead leaching.
pH Adjustment-Lime and Soda-Ash Addition.	Increase pH using Lime and Soda Ash, water becomes less corrosive.	Most effective in waters with low hardness and low pH.	Possible increase in trihalomethane formation; 30% decrease in chlorine effectiveness; slight increase in sodium.	Calcium and magnesium levels increased.	Reduce cadmium and lead leaching.
Corrosion Inhibitor-Addition of Silicates.	Formation of a protective film on pipe surfaces, which reduces corrosion.	Increased potential for deeper pits in galvanized and steel pipes.	No adverse effect; slight increase in sodium levels if sodium silicate is used.	No effect; will not increase calcium or magnesium levels.	Reduce cadmium and lead leaching.
Corrosion Inhibitor-Addition of Polyphosphates.	Formation of a protective film on pipe surfaces, which reduces corrosion.	Increased potential for algal growth in storage reservoirs and receiving bodies.	May have adverse effect on taste and odor of treated water.	Calcium levels increase. Magnesium levels will not be affected by treatment.	Reduce cadmium and lead leaching.

1/ Class 1: One or more of the major components of hard water (calcium and/or magnesium) that are present in lower amounts in soft water are protective.

2/ Class 2: Assumption not documented due to lack of supporting evidence.

3/ Class 3: One or more of the components in soft water are harmful--this includes metal ions leached from the distribution system (Cadmium, Copper, Lead, Beryllium).

TABLE 4-5

PERCENT OF SYSTEMS USING CORROSION
CONTROL IN PRIMARY WATER SOURCE--1975

		Surface Systems			Ground Systems	
Treatment Type	Percentage Using Treatment	# Systems Responding	# Systems Using Treatment	Percentage Using Treatment	# Systems Responding	# Systems Using Treatme
Corrosion Control	18%	224	41	14%	622	85

SOURCE: EPA "Survey of operating and Financial Characteristics of Community Water Systems" to attack by corrosive water. Additionally, a significant amount of corrosion due to natural pipe deterioration (from water abrasiveness) will have occured over this amount of time, further increasing the need for some type of corrosion control.

4.4.2 pH Adjustment

Soft water is often characterized by acidic conditions, so stabilization of soft water usually involves an upward adjustment of pH. Stabilization refers to an equilibrium in the calcium carbonate/bicarbonate reaction:

$$CaCO_3 + H^+ \rightleftarrows Ca^{++} + HCO_3^-$$

If the reaction proceeds to the left, especially when driven by basic conditions, a protective seal of calcium carbonate is deposited on pipes in contact with this water, thereby reducing corrosion rates. However, if the reaction proceeds to the right (usually under acid conditions), the scale is dissolved, leaving pipe surfaces susceptible to corrosion. At equilibrium, water neither dissolves nor deposits calcium carbonate, thus stabilizing the protective layer of calcium carbonate. Calcium carbonate stabilization is dependent upon several factors, mainly pH, alkalinity and calcium concentration, but also including temperature and the presence of other dissolved materials such as chlorides and sulfides. Thus, to maintain or reach stabilization, adequate alkalinity and calcium combined with the proper pH range are essential. Aside from stabilization, pH adjustment also is useful in decreasing the solubility of metals subject to corrosion.

Four methods of pH adjustment are in use--addition of lime, calcium carbonate, sodium hydroxide, or soda-ash. All but sodium hydroxide addition adds either reactants and/or products to the carbonate equilibrium and thus are effective in waters deficient in hardness or alkalinity. Lime ($Ca(OH)_2$) addition not only raises pH but adds calcium ions and is useful where a calcium deficiency exists. Carbonate concentrations,

TABLE 4-6
PERCENT OF SYSTEMS USING CORROSION
CONTROL BY POPULATION CATEGORY
1975

	Population Category									
Treatment	25-99	100-499	500-999	2,499	1,000-4,999	5,000-9,999	10,000-99,999	100,000-999,999	1 million	Average for all Systems
Corrosion Control	2	3	12	13	29	41	36	68	91	25

SOURCE: EPA "Survey of Operating and Financial Characterisitcs of Community Water Systems".

TABLE 4-7

AVERAGE AGE OF WATER SYSTEMS (YEARS)

IN 1976

	Population Category								
	25-99	100-499	500-999	1,000-2,499	2,500-4,999	5,000-9,999	10,000-99,999	100,000-999,999	1 millic
verage Age (years)									
'11 Systems	18	24	32	38	47	46	64	81	95
Public	30	30	36	42	48	48	62	77	100
# obs.)	(8)	(78)	(47)	(69)	(41)	(29)	(43)	(112)	(5)
Private	18	21	20	25	40	22	75	97	72
# obs.)	(124)	(120)	(16)	(15)	(8)	(2)	(11)	(19)	(1)
Median Age (year)									
l1 Systems	11	15	26	39	47	38	65	84	94-

SOURCE:- EPA "Survey of Operating and Financial Characteristics of Community Water Systems.

if low, may still limit achievable stability. Calcium carbonate addition raises pH and provides both calcium and carbonate to the water. Since this provides all reactants necessary for calcium carbonate stabilization, effective stabilization can be induced regardless of the ambient water quality. AWWA recommends 80-100 mg/l $CaCO_3$ as the optimal water hardness to achieve stability. Soda-ash addition raises pH and bicarbonate content. This may be used in combination with lime if calcium is also deficient. Sodium hydroxide addition acts solely to raise pH and will not be very effective if adequate calcium or carbonate is lacking. However, this addition will decrease the corrosion of metals somewhat as their solubility will decrease with increasing pH.

4.4.3 Corrosion Inhibitors

Addition of corrosion inhibitors is another effective method of corrosion control. Two major types of inhibitors exist--polyphosphates and silicates--and through deposition of a thin film, they act to significantly reduce corrosion. Although the two inhibitors are similar in action, they work under slightly different mechanisms. Corrosion inhibitors can be economically advantageous over additives which adjust pH becuase inhibitors are normally utilized in low dosages (under 5 mg/l) while pH adjustment additives are applied in macroconcentrations (around 50 mg/l).

Several different types of polyphosphate are being marketed for corrosion control use, of which zinc poly- or orthophosphate are purported to be most effective. Polyphosphates react with iron and other minerals in water, forming a positively charged particle. This particle migrates to the cathodic area of a corrosion "cell" and forms a thin protective film which reduces corrosion. Once this film is established, dosages can be lowered somewhat. Maximum systemic temperature, pH, retention time and sealing potential all affect the performance of polyphosphate additions. Generally, optimal performance is reached above pH 7.0.

Silicates function through absorption onto the corrosion products (oxides) of iron and zinc. Their effectiveness is dependent upon continuity of treatment and systemic water velocity. This treatment is commonly used for waters having a pH less than 8.4 and very low hardness.

4.5 COST OF CORROSION CONTROL TECHNOLOGIES

4.5.1 Introduction

Internal corrosion causes economic losses in municipal water supply system which can be prevented with the implementation of a cost-effective corrosion control program. The mechanism utilized to reduce the losses from corrosion is dependent on several factors, some of which include the characteristics of the water treated, cost of the various chemicals used, and the capital costs. A very limited number of studies by MRI, EPA and the City of Seattle have been conducted to investigate the costs of corrosion control programs. Costs associated with various programs implementing either pH adjustments with lime addition, or corrosion inhibitors including silicate or polyphosphate will be discussed below.

4.5.2 Result of Findings

An estimation of corrosion control costs was determined by contacting drinking water treatment facilities which use corrosion control and chemical companies that produce corrosion inhibitors. A capital recovery factor was assumed to be 30 years at 8 percent interest in order to be consistent with other studies. A breakdown of the costs is displayed in Table 4-8.

Bimetallic polyphosphate addition was the most expensive means of controlling corrosion as a result of the greater chemical costs. The cost analysis assumed a bimetallic polyphosphate level of 1.5 parts per million. This level was determined to be effective given most water supply characteristics. Bimetallic polyphosphate is a much more effective means of controlling corrosion, as the zinc addition allows the film to form more rapidly and has lower dosage requirements as compared to the addition of polyphosphate alone. The cost was estimated to $0.47 per capita per year for the addition of bimetallic polyphosphate. Sodium silicate is not commonly used as corrosion inhibitor, yet from the cost analysis it was determined to be the least expensive. The initial level must be 24 parts per million of silica for the effective formation of the film and thereafter the silica level should be maintained at 8 parts per million. The sodium silicate method of treatment is quite similar to the polyphosphate method and therefore operational and maintenance costs were assumed to be the same. A cost of $0.185 per capita per year was estimated to be the cost for sodium silicate used as a corrosion inhibitor.

Lime addition is another method of treatment to control corrosion. Dalecarlia Drinking Water Facility in Washington, D.C. uses lime as a corrosion inhibitor. The pebble lime that is used must contain 90 percent calcium oxide. The Langlier saturation index (LSI) is used to determine the level of lime saturation and the water is maintained at the saturation level at all times. This method of treatment is very effective in controlling corrosion at Dalecarlia. The estimated cost for corrosion control treatment through the addition of lime amounts to $0.21 per year per capita. As evident in Table 4-8 the unit process costs which include contingencies, engineering and administration, sitework, electrical and chemical feed equipment costs are much greater when using lime as compared to polyphosphates or silicates. The increase in costs result from the higher dosage requirements which increase the unit process costs. However, the use of lime to adjust the pH of aggressive waters is one of the most proven methods of corrosion control. A summary table of corrosion control mechanisms and treatment cost is displayed in Table 4-9.

TABLE 4-8

CORROSION CONTROL MECHANISMS COSTS PER CAPITA PER YEAR

	Polyphosphate[1/]	Sodium Silicate[2/]	Lime[3/]
Enclosure	$4,600.0	$4,600.0	$3,600.0
Unit Process	3,700.0	3,700.0	10,500.0
Capital Cost	8,300.0	8,300.0	14,100.0
x .0883[4/]	$ 732.89	$ 732.89	$ 1,252.5
Power	$110.0	$10.0	$105.0
Enclosure Supplies	60.0	60.0	70.0
Sub total	170.0	170.0	175.0
Capital Cost	732.89	732.89	1,252.5
	$902.89	$902.89	$1,427.5
Sub total of per capita cost	$0.09	$0.09	$0.14
Chemical cost	0.38[5/]	0.095[6/]	0.07[7/]
Per capita cost per year	$0.47	$0.185	$0.21

1/ Assume 1.5 parts per million of zinc polyphosphate.

2/ Assume 8 parts per million silica.

3/ Assume 50 milligrams per liter of lime.

4/ Assume a capital recovery factor of 30 years at 8 percent

5/ Calgon Chemical Company.

6/ Philadelphia Quartz Company.

7/ Delcarlia Drinking Water Facility.

SOURCE: EPA "State of the Art of Small Water Treatment Systems" August 1977. EEA.

4.5.3 Summary of Past Studies

All of the cost analysis of various corrosion treatment methods incorporate the same economic considerations. The cost breakdown is composed of chemical costs, capital costs, labor costs and maintenance costs. MRI determined that chemical costs range from 46.0 percent to 76.9 percent, labor costs range from 4.6 percent to 13.1 percent and maintenance costs range from 1.9 percent to 4.3 percent. The percentage variance is dependent on the method of control implemented, which in turn is dependent on the corrosive properties of the water.

The water can become less corrosive and more stable by adjusting the pH. The two types of treatment considered by MRI were pH adjustment, either through the addition of lime (Treatment 1) or through the addition of lime and carbon dioxide (Treatment 2). MRI conducted a study of the major water utilities in the United States and determined the costs for the two types of treatment that were the most common from their survey. Several conditions were necessary for each one of the treatments to be effective against corrosion. Stabilization of the water by Treatment 1 requires an LSI of 0.0. If an LSI of 0.0 is not reached when the pH is at 9.5, then carbon dixoide is added to maintain the pH level at 9.5. The average per capita cost for this treatment is $0.14 per year. The range of cost varies from $0.03 and $0.69 per year depending on the corrosivity characteristics of the treated water. Treatment 2 is more costly than Treatment 1 because of the increase in chemical costs. In order for this treatment for corrosion control to be effective a final LSI of 0.0 is also required with a minimum alkalinity value of 40 mg of $CaCO_3$ per liter and a minimum calcium content of 16 mg of Ca per liter. The final pH of 7.3 or below or a pH of 8.6, was also necessary. Lime and carbon dioxide were the chemical additions to achieve stabilization. An average annual cost of $0.42 was determined for this treatment with a range of per capita costs of $0.04 to $2.69 per year. The reason for this discrepancy in costs is because of the increase in chemical costs from Treatment 2.

TABLE 4-9

SUMMARY OF WATER TREATMENT MECHANISMS AND COSTS

T[illegible]tment Methods Water	Treatment Mechanisms	Affect on pH	Affect on Alkalinity	Possible Adverse Health Effects	Conditions for Effective Treatment	Operational & Maintenance Cost Per Capita Per Year	Capital Cost Per Capita Per Year	Chemical Cost Per Capita Per Year	Total Cost Per Capit Per Year
pH Adjustment-L[illegible] Addition	Increase pH and calcium content, enhances calcium carbonate deposition.	Significant increase in pH levels.	Increase alkalinity levels.	Possible increase in trihalomethane formation, a suspected carcinogen; 30% decrease in chlorine effectiveness.	Most effective in waters with low hardness and low pH. Adequate carbonate levels are required.	$0.02	$0.12	$0.07	$0.21
p[illegible] [illegible]djustment-Sodium Hydroxide or Soda-A[illegible] Addition	Increase pH and/or carbonate content, enhances calcium carbonate deposition.	Significant increase in pH levels.	Increase alkalinity levels.	Possible increase in trihalomethane formation; 30% decrease in chlorine effectiveness; slight increase in sodium, which is related to hypertension.	Most effective in waters with low pH and adequate calcium levels.	NA	NA	NA	NA
p[illegible] [illegible]djustment-L[illegible] and Soda-Ash Addition	Increase pH, calcium, and carbonate content enhances calcium carbonate deposition.	Significant increase in pH levels.	Increase alkalinity levels.	Possible increase in trihalomethane formation; 30% decrease in chlorine effectiveness; slight increase in sodium.	Most effective in waters with low hardness and low pH.	NA	NA	NA	NA
Corrosion Inhibitor Addition o[illegible] [illegible]ilicates	Formation of a protection film on pipe surfaces which reduces corrosion.	Slight increase in pH levels.	Slight increase in alkalinity levels.	No adverse effect; slight increase in sodium levels if sodium silicate is used.	Most effective in water with low hardness and a pH of less than 8.4	$0.02	$0.07	$0.095	$0.185
C[illegible]rosion Inhib[illegible]r Addition of Polyphosphates.	Formation of a protective film on pipe surfaces which reduces corrosion.	No effect on pH levels.	No effect on alkalinity levels.	May have adverse effect on taste and odor of treated water.	Adjustment of pH levels above 7.0 are required for effective treatment.	$0.02	$0.07	$0.38	$0.47

[illegible] NA: Not applicable.

SOURCE: EEA

Hudson and Gilcreas did a study on the economics of water hardness corrosivity. It was determined that the cost of stabilization of water would be $27 million annually or an average of $0.13 per capita per year. The source did not describe the type of corrosion treatment that was assumed in the calculation and which can vary significantly from treatment to treatment.

The Seattle corrosion control plan resulted from an investigation of the corrosion problems within the Seattle distribution system. The proposed program will raise the pH and alkalinity of the water. Silicate may also have to be added to the Tolt supply to bring it up to the concentration found in the Cedar supply. Calcium oxide, sodium bicarbonate and sodium silicate are added to the water supply to increase the pH and lower the corrosivity characteristics. The study determined the cost of a corrosion control program in Seattle would amount to $0.41 per year per capita. This study estimated that the chemical cost comprises 70 percent of the total annual cost. A factor which was difficult to estimate was the severe deterioration that has already occurred due to the corrosivity of the water in the older section of pipe and plumbing. Therefore the unit cost for plumbing and maintenance will be higher for older systems.

4.6 BENEFIT-COST ANALYSIS

4.6.1 Introduction

Internal corrosion causes economic losses in municipal water supply systems. The implementation of a cost-effective corrosion control program can offset the economic losses of corrosion. An annual financial benefit would be received equal to the economic value of the internal corrosion that was avoided. The economic benefit-cost analysis of corrosion control programs varies depending on the corrosion studies used. MRI, EPA and the Seattle corrosion studies estimated the costs of implementating of a corrosion control program and these findings will be discussed below.

4.6.2 Analysis

An estimation of all the costs associated with corrosion and pipe degradation amounts to an annual cost of \$2.67 per capita. This estimation was determined from various economic analysis on the costs of corrosion. A benefit-cost analysis will be determined from the estimation of corrosion control costs for drinking water treatment facilities and treatment chemical companies and the annual cost of corrosion per capita. The benefit cost ratio varies from 5.7:1 to 14.4:1, depending on the type of treatment implemented as shown in Figure 4-5.

The treatment utilizing zinc polyphosphate as a corrosion inhibitor is the least cost-effective. The economic benefit-cost ratio is the lowest, when compared to the other treatments evaluated, due to the greater chemical costs associated with this type of treatment.

1. Treatment with the addition of zinc polyphosphate.

   Benefit = Nationwide annual cost of corrosion per capita.

   Cost = Nationwide annual cost of corrosion control treatment using polyphosphates per capita.

$$B/C = \frac{2.67}{0.47} = 5.7$$

Sodium silicate used as a corrosion inhibitor is the most cost-effective. This benefit-cost analysis ratio is 14.4:1 and is greater due to the lower chemical costs when compared with polyphosphates.

2. Treatment with the addition of sodium silicate.

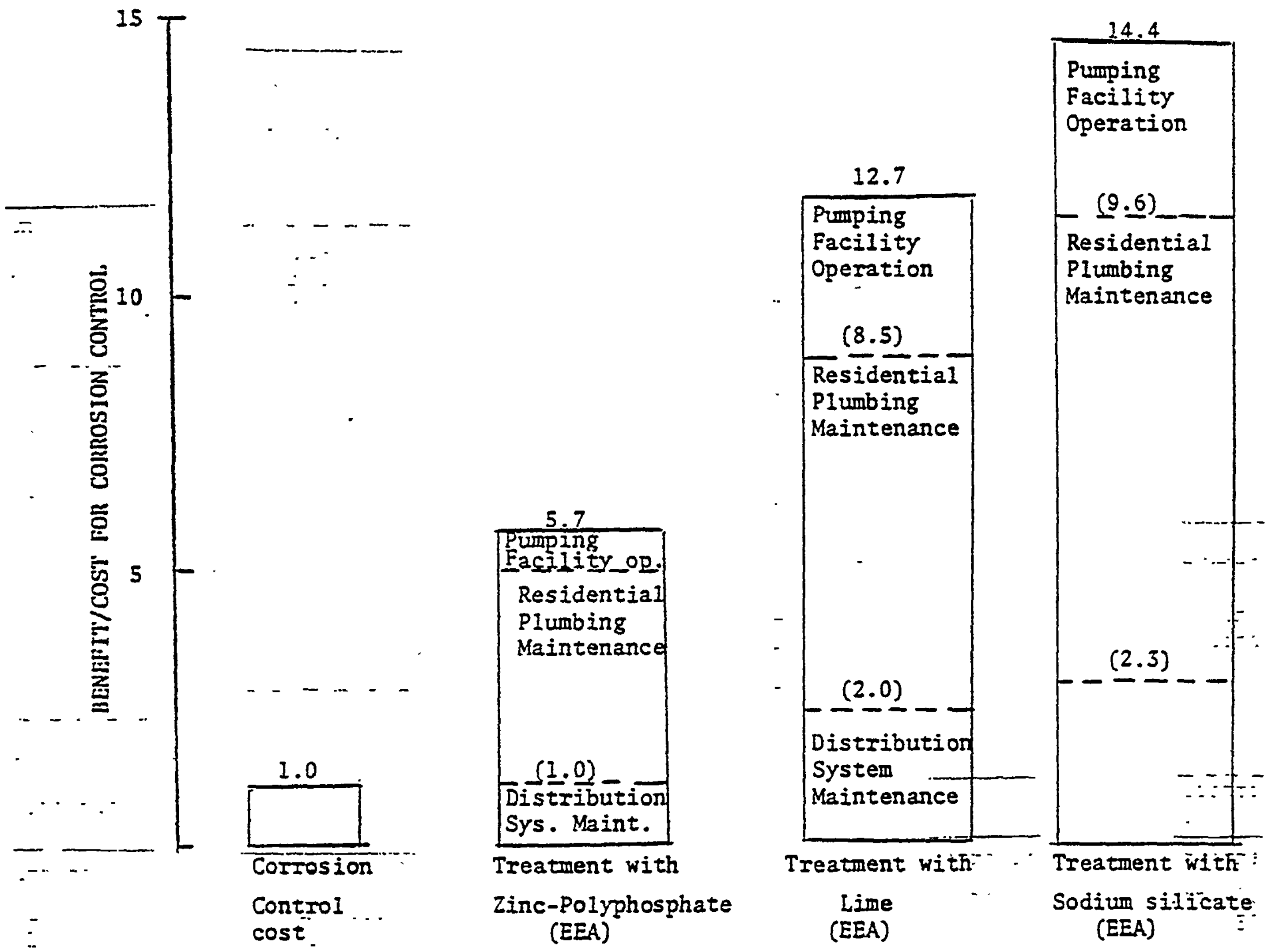
   Benefit = Nationwide annual cost per capita of corrosion.

   Cost = Nationwide annual cost per capita of corrosion control using sodium silicate.

$$B/C = \frac{2.67}{0.185} = 14.4$$

FIGURE 4-5

PIPE SAVINGS FROM CORROSION CONTROL



SOURCE: EEA

Lime addition used to adjust the pH is the most common method to control corrosion and is very cost-effective. The benefit-cost analysis ratio is 12.7:1 and is less than the sodium silicate analysis because of the greater unit process costs.

3. Treatment with the addition of lime.

   Benefit = Nationwide annual cost per capita of corrosion.

   Cost = Nationwide annual cost per capita of corrosion control using lime.

$$B/C = \frac{2.67}{0.21} = 12.7:1$$

Sodium silicate used as a corrosion inhibitor is more cost-effective than lime addition. However, an upward adjustment of pH is more widely utilized as a corrosion control mechanism and is more effective. There are also greater health benefits associated with the elements found in lime as opposed to those found in sodium.

4.6.3 Analysis of Past Studies

MRI conducted a nationwide utility survey to determine a benefit-cost ratio between the costs of corrosion compared with the costs of corrosion control. The program utilizing Treatment 1 (as discussed in Section 4.5) has a benefit cost ratio of 3.8:1 or 4.8:1, depending on the treatment used, as shown below.

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

   Cost = Treatment 1 cost of stabilization

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

5. Benefits = best estimate of losses less 50 percent of losses of steel/galvanized pipe.

   Cost = Treatment 1 cost of stabilization

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

However, the benefit cost ratio is much less when Treatment 2 is implemented to control corrosion due to the increased chemical costs. The benefit-cost ratio for Treatment 2 is either 1.2:1 or 1.5:1.

6. As in (1) with Treatment 2 for stabilization.

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

7. As in (2) with Treatment 2 for stabilization.

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

Hudson and Gilcreas determined from their study that a benefit cost ratio of 13.9:1 exists for the implementation of cost-effective corrosion control program.

8. Benefits = Nationwide cost of corrosion.

   Cost = Nationwide cost for corrosion control (source did not mention type of treatment considered).

$$B/C = \frac{375,000,000}{27,000,000} = 13.9$$

The Seattle corrosion control study determined that the cost of the implementation of corrosion treatment on the Tolt and Cedar Rivers would amount to an annual cost of $508,500. The cost of corrosion in Seattle amounts to $7,800,000 annually. This equals a benefit-cost ratio of 15.4:1.

9. Treatment with the addition of calcium oxide, sodium bicarbonate and sodium silicate.

   Benefit = Seattle's annual economic losses due to corrosion.

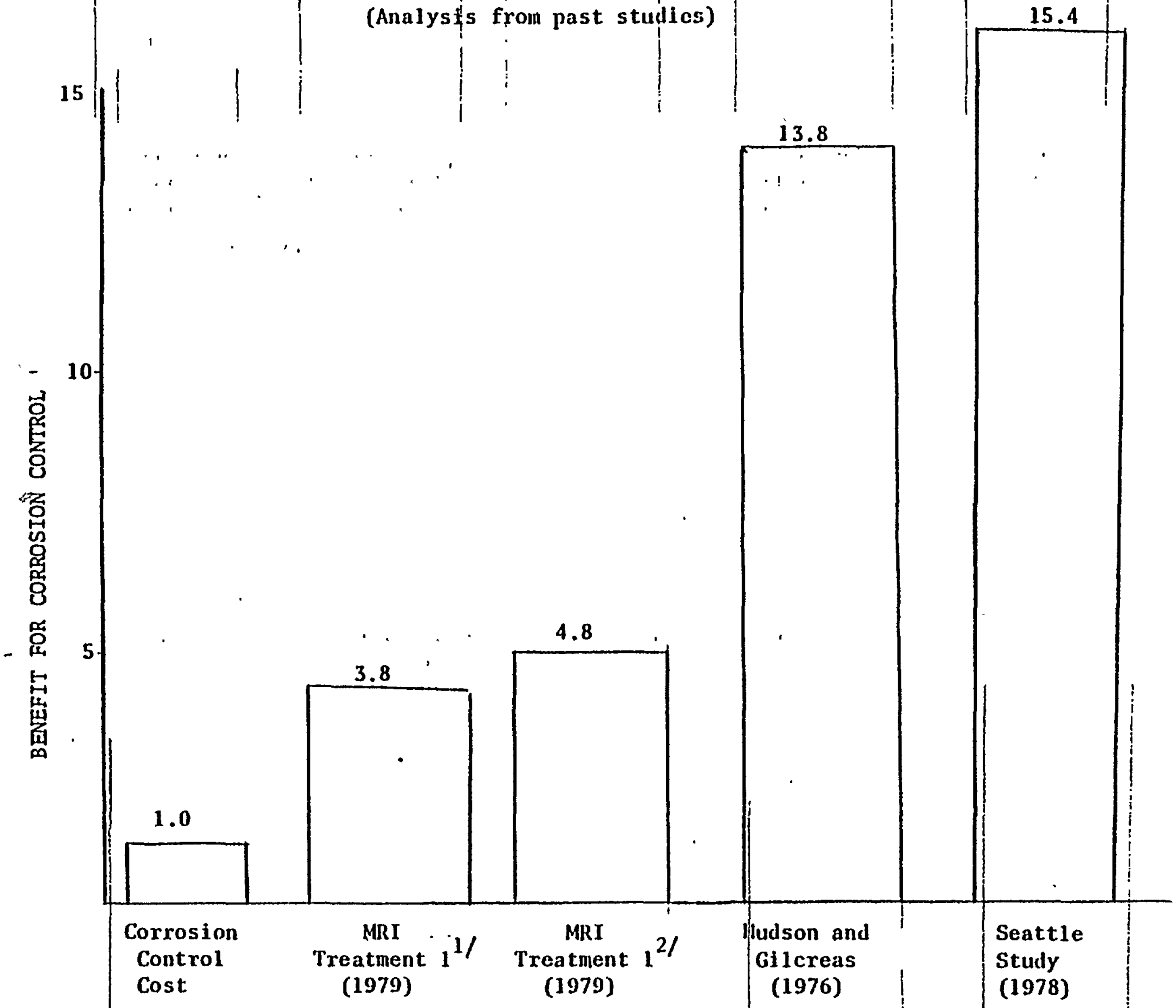
   Cost = Seattle's annual cost for the implementation of the proposed corrosion control program.

$$B/C = \frac{7,800,000}{508,000} = 15.4$$

A graphic representation is shown in Figure 4-6 of various estimates of pipe savings from corrosion control.

FIGURE 4-6

PIPE SAVINGS FROM CORROSION CONTROL
(Analysis from past studies)



1/ Treatment assumes benefits = best estimate of losses less losses of steel/galvanized pipe.
2/ Treatment assumes benefits = best estimate of losses less 50% of losses of steel/galvanized pipe

5. SUMMARY AND CONCLUSIONS

Medical studies have shown a correlation between soft water and cardiovascular diseases (CVD). Since 55.3 million people depend upon soft water for their drinking water, the potential health risk is significant. Water hardening treatment can lessen these potential adverse health impacts. Lime addition is an effective hardening treatment giving health benefits much greater than the cost of the treatment. By increasing the hardness by such treatment in soft water areas, over 13,800 deaths could potentially be prevented annually. This represents a reduction in the national overall death rate by 2.8 percent in soft water areas.

Technology to increase water hardness is available and economically feasible. Not only could the use of this technology result in a significant public health benefit, but it would also have the additional benefit of lowering pipe corrosion in water distribution systems. Soft or corrosive water causes a substantial increase in operation costs due to early pipe replacement, water loss, and increased energy usage. As a result the benefit to cost ratio to control corrosive water is approximately 3.0:1.

Therefore, the implementation of a water treatment program to harden soft water or stabilize corrosive water will yield both a health and cost advantage to the population exposed to soft water. Twenty-seven percent of the United States population are dependent on soft drinking water. EPA has the authority in the Safe Drinking Water Act to include a minimum hardness requirement and to establish an MCL based on corrosion indices. This authority should be exercised given the potential adverse health effects of increased cardiovascular disease in soft water areas to protect the public heath. Given the large percentage of the United States population exposed to soft water, a minimum hardness requirement or a corrosivity MCL should be implemented nationwide.

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APPENDIX A

APPENDIX A

In order to determine the percentage of the United States population exposed to soft water several different sources were utilized.

STEP 1: IDENTIFICATION OF SURFACE SOFT-WATER AREAS. Surface soft-water areas were identified using a U.S.G.S. report entitled "Quality of Rivers of the United States, 1975 Water Year--Based on the National Stream Quality Accounting Network (NASQAN)." A U.S. map displaying concentrations of hardness as calcium carbonate in milligrams per liter was used to identify soft-water surface areas.

STEP 2: IDENTIFICATION OF GROUND SOFT-WATER AREAS. A Water Information Center Publication entilted "Water Atlas of the United States," published in 1973, contained a map (Plate 42) displaying groundwater hardness expressed as parts of $CaCO_3$ per million. From this map, soft groundwater areas were identified.

STEP 3: IDENTIFICATION OF SOFT-WATER COUNTIES. Counties containing surface and ground soft-water were identified using the 1972 edition of the U.S.G.S. publication of "Maps Showing Locations of Stream Flow and Stage Stations." Maps were divided into Water Resource Regions, the same division used in the surface water hardness map.

STEP 4: POPULATIONS LOCATED IN SOFT-WATER COUNTIES. The populations located in surface or ground soft-water counties was determined from the 1970 edition of the Rand McNally's "Road Atlas-United States-Canada-Mexico."

STEP 5: DETERMINATION OF PERCENTAGE OF STATE POPULATIONS USAGE OF SURFACE OR GROUNDWATER. A percentage of the total state population utilizing either surface or ground water was determined from the "Estimated Use of Water in the United States in 1970," a U.S.G.S. circular number 676, Figure 5.

STEP 6: ACTUAL PERCENTAGE OF STATE UTILIZING SOFT SURFACE OR GROUNDWATER. The soft-water county figures determined by state, were then multiplied by the appropriate surface or groundwater percentage number to determine the approximate percentage of the state population utilizing either surface or ground soft-water.

STEP 7: ACTUAL PERCENTAGE OF STATE UTILIZING SOFT SURFACE OR GROUNDWATER. The state population utilizing soft-water was then divided by the total state population to determine the percentage of the state exposed to soft water.

SETP 8: REGION IDENTIFICATION. The three regions identified were divided into the eastern, southern, and western regions respectively.

STEP 9: PERCENTAGE OF UNITED STATES POPULATION EXPOSED TO SOFT-WATER IN 1970. The number of the U.S. population exposed to soft-water was determined by adding up the state populations and obtaining a U.S. population exposed to soft-water. A percentage of the U.S. population was obtained by dividing the U.S. soft-water population by the 1970 total population.

Given the limitations regarding precision of the method employed, approximately 27 percent or 56 million of the total 1970 United States population was estimated to be exposed to naturally soft-water. The eastern region amounted to 55 percent of the total soft-water areas, about 38 percent in the south, and the western region only amounted to 7 percent of the soft-water population.