TOWARDS A NATIONAL INFRASTRUCTURE STRATEGY: WATER DISTRIBUTION SYSTEMS - A CASE STUDY

by

RANDALL JAMES BORAS

B.Sc., The University of Alberta, 1986

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF

THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

in

THE FACULTY OF GRADUATE STUDIES

THE SCHOOL OF COMMUNITY AND REGIONAL PLANNING

We accept this thesis as conforming

to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA

April 1994

Abstract

Treated water distribution systems in North America represent a major component of the physical infrastructure in dire need of closer attention by the regulatory bodies, local, regional and national governments, and the public in general. The problems identified by the media over the past decade have been limited to pictures of collapsing or deteriorating pipes. The real problems run much deeper. Reduced government funding over the years, changing public priorities, and a lack of comprehensive information required to accurately define the problems have plagued the overall management of water systems in Canada and the United States.

This thesis provides an overview to municipal water distribution systems in Canada, investigating not only the physical processes responsible for the deterioration of such systems, but the historical impetus associated with the development of such systems, the physical profile of the systems unique within Canada, the changing social environment surrounding aged systems, and the real costs associated with repairing worn out systems. Existing historical information is gathered from a variety of sources to profile the Canadian systems. Research by governments and lobby groups, especially the Federation of Canadian Municipalities, is reviewed and summarized. Technical information and current techniques for managing individual water systems are also reviewed. The information is then sysnthesized into a number of policy suggestions aimed at effective solutions to the current crisis and reviewed within the context of a small community in Greater Vancouver.

There is no single magic formula to solving the problems, but rather a wide and

varied combination of improvements which must be made over the broad spectrum of water distribution system management. National, provincial, and local bodies are all involved to some degree in the management decisions and all could utilize more effective management techniques which focus on better implementing already available technologies rather than developing new technologies. Rehabilitation decisions must be based on sound principles aimed at effectively protecting public interests, rather than techniques which are often geared more to the availability of grants rather than the actual condition of the pipes.

Information important to the decision making process must, however, not be restricted to the decision makers. Polls have shown that public interest and concern over drinking water issues is typically very low, and is only heightened by crisis-type situations. This was very evident in the recent federal election, where suggestions by the Liberal party to implement an infrastructure program were often met by ridicule and cynicism, considered as opportunistic spending aimed only at securing the votes of the unemployed, rather than any legitimate concern for public health or economic benefit.

In recent months the Liberal party has formed the new federal government and has committed an infrastructure program, having set aside \$2 billion to solving what may now be a \$30 billion infrastructure problem in Canada. To maintain the public faith and to assure these limited funds are used effectively, there is a real need for improved policies. This thesis will endeavour to provide the basic framework for a national policy to better manage the present and the future of the conduits which carry the gift of human life through our towns and cities - good, wholesome, clean, drinking water.

TABLE OF CONTENTS

CHAPTER 3: CANADIAN WATER DISTRIBUTION SYSTEMS INVENTORY

CHAPTER 4: WATER MAIN DETERIORATION

CHAPTER 5: CONDITION ASSESSMENT AND MITIGATIVE TECHNIQUES

LIST OF TABLES

LIST OF FIGURES

Acknowledgements

I am deeply grateful to a number of people who guided, questioned, challenged, and supported me throughout the last few years. I am especially thankful for the assistance of the faculty at U.B.C. especially Prof. Setty Pendakur, in the School of Community and Regional Planning, and Prof. Frank Navin, in the Department of Civil Engineering, who were not only valuable in guiding my work, but also assisted me in securing financial assistance. I am grateful to the Natural Sciences and Engineering Research Council for having the confidence in me to provide the scholarship to carry out my research. I am also indebted to the late Bill Curtis, the former City Engineer at the City of Vancouver, whose total and long-time commitment to solving the current problems and thoughtful insight and vision for the future guided my course. I am deeply grateful to the numerous faculty members, municipal employees, and government officials who provided data, interviews, and spare time to assist me in putting this thesis into perspective. I would also like to thank MPE Engineering Ltd. for providing assistance and understanding along the way. Finally, to my friends and family I owe my deepest thanks. Mom and Dad this is especially for you.

CHAPTER 1: INTRODUCTION

1.0. Introduction

Media exposure in North America over the past decade has presented images of deteriorating bridges, clogged roadways, overcrowded airports, and collapsing water systems, graphically defining the term "infrastructure deterioration." A combination of funding shortfalls, political shortsightedness, and poor planning is blamed for many of the problems. In Canada, serious concern over the unacceptable decay of urban public systems has surfaced over the past eight or nine years. Much of the current problem is rooted in policy shifts dating back to the late 1960s and early 1970s which have led to reduced spending on system rehabilitation and replacement.

In 1984 the Federation of Canadian Municipalities (FCM 1984) conducted a survey of 63 municipalities and estimated that $598 per capita, or over $10 billion nationally, was required to rehabilitate six major urban public facilities: roads, sewage collection, water distribution, sewage treatment, water treatment, and bridges. Since that time, from a provincial perspective, only Alberta has expanded its capital funding programs to include rehabilitation of existing works, leading the FCM to conclude in 1991 that overall the situation is not improving, but rather becoming worse (Curtis 1991b). Taking into account inflation and the additional deterioration since the 1984 report, there may now be as much as $15 to $20 billion worth of work waiting to be done and some feel the number may be as high as $30 billion (Mavinic 1990).

The recent two year $2 billion federal contribution to a new infrastructure program announced by the newly elected Liberal government represents a significant shift in policy, which over the past decade has been dominated by the thinking that infrastructure problems were largely provincial and local matters. Prime Minister Jean

Chretien's new program will adopt the funding formula advocated by the Federation of Canadian Municipalities, a formula based on equal contributions by federal, provincial, and local government. Unfortunately, the reality of increasing debt loads at both the provincial and local levels may make it difficult to carry out the required work. From an overall perspective, the new program will only address a fraction of the problems identified almost a decade ago by the FCM. For this reason, the limited resources now being directed toward the problem must be used in the most effective way possible. A good understanding not only of the physical engineering aspects of deteriorating infrastructure systems, but of the overall political, environmental, and financial climates is key to making the most of the current opportunity. Unfortunately, even with the recent work over the past decade by the FCM, there remains major gaps in even the most basic information regarding the condition of our infrastructure systems and there remains major inadequacies in the management of such systems.

The aim of this thesis is to paint a clear picture of current infrastructure management in Canada. To date, a very broad brush has been used to illustrate the problems, concentrating more on identifying the multi-billion dollar backlog of work and how to pay for it, with less attention to the details of how we got in this mess, where we are going now, and how we can do things better to get out of it. This thesis will contribute by exploring the scale, context, and nature of the problems through a detailed study of one particular component of our overall physical infrastructure: treated water distribution systems.

Currently, deteriorating systems are being maintained far past their economically effective life, with already scarce time and monetary resources being used to hold together system components that should have been replaced long ago. A shift away from the prevalent social, political, and financial emphasis on growth and expansion of new facilities which began after World War II, to one of effective maintenance, reconstruction and renovation of existing facilities is now required. This can and should be achieved by a number of means, apart from the most obvious infusion of huge amounts of capital from debt-burdened provincial and federal sources: application of better information systems to allow effective monitoring of infrastructure condition; improved techniques for determining optimum rehabilitation and replacement scheduling; more effective pricing of water to reflect the true value of the resource; and increased public awareness to both reduce the demand on overworked systems and to increase the funds available for maintenance and repair. The current philosophy of design which aims at satisfying ever increasing user demands through ever expanding systems must shift to one which recognizes the need for conservation and more effective use of both the water and the system carrying it. Historically a local concern, water distribution systems still serve sufficient interests at both the provincial and federal levels to merit continued involvement by all levels of government.

Technical, financial, political and social concerns are reviewed to develop a rational framework which can be utilized to help manage the problems and improve the systems. At the local level, the framework stresses the importance of improving both supply side and demand side management of water distribution systems. At the provincial and national level the framework emphasizes increased technical support and management guidance, as well as appropriate financing assistance.

The water distribution system of a small Canadian community is then profiled within the context of the framework to investigate the potential application and specific problems which must be resolved.

This thesis, while ultimately aimed at senior federal and provincial policy makers, is written and presented to allow a basic understanding of infrastructure management problems by post-graduate planning and engineering students, professional planners and engineers, and decision makers involved on a day to day basis with managing and maintaining infrastructure systems. The thesis purposely focuses on both technical and non-technical factors which equally contribute to today's situation.

The thesis will concentrate on improving existing water systems which require rehabilitation or replacement because of deterioration or regulatory obsolescence. Some attention will be given to the problems encountered by communities experiencing rapid growth where diminishing system capacities and continued system expansion are major concerns. However, the major emphasis will be on planning for the continued use of existing systems rather than on the problems associated with growth, a subject which in itself is sufficiently complex to merit study on its own.

While this thesis admittedly does not provide all the solutions to water distribution infrastructure in Canada, it does examine a number of the problems with infrastructure management in general. This thesis is meant to provide a clearer picture of the problems being dealt with, rather than represent the final solution. As such, it symbolizes a small, though not insignificant, piece to the whole puzzle.

1.1. Methodology

The methodology of this thesis consists of five basic components pertaining to water distribution systems both in general terms and terms more specific to the Canadian context:

1) a literature review of recent trends and developments pertaining to water systems,
2) establishment of baseline information for discussion of Canada's water distribution systems,
3) development of a rehabilitation policy framework for application within Canada,
4) discussion of a case study within the context of the policy framework, and
5) final conclusions and recommendations.

The literature review includes an examination of the water distribution systems in Canada: the historical development of them, the current legislation and standards regulating them, the major concerns regarding them, the physical mechanisms deteriorating them, and the present mitigative techniques and technology available to improve them.

The estimate of Canada's total water distribution systems draws on historical and current data to develop a national inventory of systems. The total length of the systems, as well as information on pipe sizes, material types, and age have been compiled from existing sources to provide a baseline for discussion of policies aimed at the particular problems and specific needs of different communities and regions in Canada.

A general framework for water distribution system rehabilitation applicable to the Canadian context is then formulated from the information reviewed. The framework basically involves the application of demand management principles and appropriate state-of-the-art rehabilitation and replacement models to Canadian systems.

Terms of the framework are then discussed relative to Pitt Meadows, a small community in metropolitan Vancouver. The discussion focuses on the applicability of techniques, the impediments to implementation, and highlights by example the specific problems which can be encountered at the community level.

The final section of the thesis includes the conclusions drawn from this study as well as recommendations aimed at the general application of such a framework within Canada.

1.2. Organization

The thesis is organized into eight chapters. Chapter one outlines the scope of the thesis, the problem statement, the methodology, and the organization. Chapter two includes a history of Canada's municipal water systems, a review of the current legislation and standards, and a look at the factors behind the need for water distribution system rehabilitation. Chapter three includes an estimate of the total water distribution systems in Canada. Chapter four is more technical in nature and outlines the deterioration mechanisms which affect pipe life. Chapter five is an overview of current state-of-the-art system condition monitoring and mitigative techniques. Chapter six outlines the development of a general framework for water distribution rehabilitation in Canada. Chapter seven includes a case study on the application and assessment of this framework to Pitt Meadows, a small municipality in Greater Vancouver. Chapter eight summarizes the findings, draws conclusions, and makes recommendations on the applicability of the framework to the Canadian scene.

1.3. An Introduction to Infrastructure

The term "infrastructure" is a generic label given to the structure of a host of systems which connect or serve human activities in some way. The systems are typically quite large and complex, and are often so deeply entrenched in the workings of everyday life that they are assumed to exist and often are taken for granted. The systems can be privately held, as are many telephone utilities and gas companies, or publicly held as are the provincial health care and highway systems.

A further distinction is made between social and physical infrastructure (FCM 1984). The social infrastructure is comprised of formal connections based less on physical structures such as pipes and cables, and more on social structures such as laws, bureaucracies, or political systems. Functions such as health care, education, police protection, and recreation are included in the social infrastructure.

The physical infrastructure, or as Adams and Heinke (1987) term it, the "civil engineering infrastructure" refers to "the extensive and costly physical facilities that provide the goods and services necessary for the functioning of modern society." It includes a vast array of systems associated with communication, transportation, transmission, production, and extraction in a variety of regional contexts as illustrated by Table 1.1.

Such systems are not only characterized by their massive scale and complexity, but also by their functional time dependence; they experience loads or demands which vary over time and as such require continuous or intermittent operation (Adams and Heinke 1987). Further, all of these systems, regardless of the degree of maintenance, will eventually wear out and need to be replaced. When this is overlooked in the initial planning and operational stages of a system, inadequate replacement programs often result. As the FCM points out, this is the case with many urban systems which are in an unchecked mode of slow decay.

Clearly an assessment of the current condition of all forms of even the public infrastructure would be an enormous task. The FCM (1984) report concentrates on the condition of urban infrastructure, which is generally within the responsibility of local government, and finds that the systems associated with the urban social infrastructure in Canada are in a relatively better condition than the physical systems.

Table 1.1: Classification of civil engineering infrastructure

Region	Public Works	Private Works
Urban	Water Distribution Sewage Collection Roads, Bridges, etc.	Structures Electrical Systems Gas Distribution, etc.
Interurban	Highways, Railways Transmission Lines, etc.	Pipelines, Railways Aqueducts, etc.
Nonurban	Dams, Reservoirs Rural Roads, Bridges, etc.	Dams, Power Plants Mining Structures, etc.

Source: Adams and Heinke (1987)

1.3.1. Characteristics Unique to Water Distribution Systems

The problems of water distribution system deterioration and infrastructure are complex, involving all levels of government and many interests, and as such require strategies based on an interdisciplinary approach including engineering, management, and policy skills (Grigg 1988, p.7).

Even other seemingly similar underground systems, such as the sewer and drainage systems, have significant functional and operational differences which make for very different deterioration and failure criteria and which require much different maintenance and rehabilitation procedures. In addition, water pipes operate under pressure and transport drinking water, two characteristics which imply a set of operational and health criteria very different from any other system.

The FCM (1984) outlines many factors which have led to the general problem of infrastructure in Canada over the past twenty years, including increased competition from expanded social programs for even scarcer funds, reduced local debt financing due to highly unstable interest rates, spiralling costs due to inflation, and increased public concern about disrupting the urban environment. But there are also characteristics of the individual systems that make each's "crisis" unique. For instance, the FCM (1984) noted that road systems and sidewalks in Canada were perceived to be in the worst condition partially due to the fact that they are highly visible, but more because they are funded from local general revenues, where competition for funds is intense. Water distribution systems on the other hand are perceived to be in relatively better condition mostly because they have their own independent source of funding in the form of "user-fees" (FCM 1984). But the fact that underground systems are buried means their true condition is not always under public scrutiny and utility managers are not faced by the barrage of day-to-day complaints associated with highly visible defects. This may tend to under-estimate the perceived needs of buried systems.

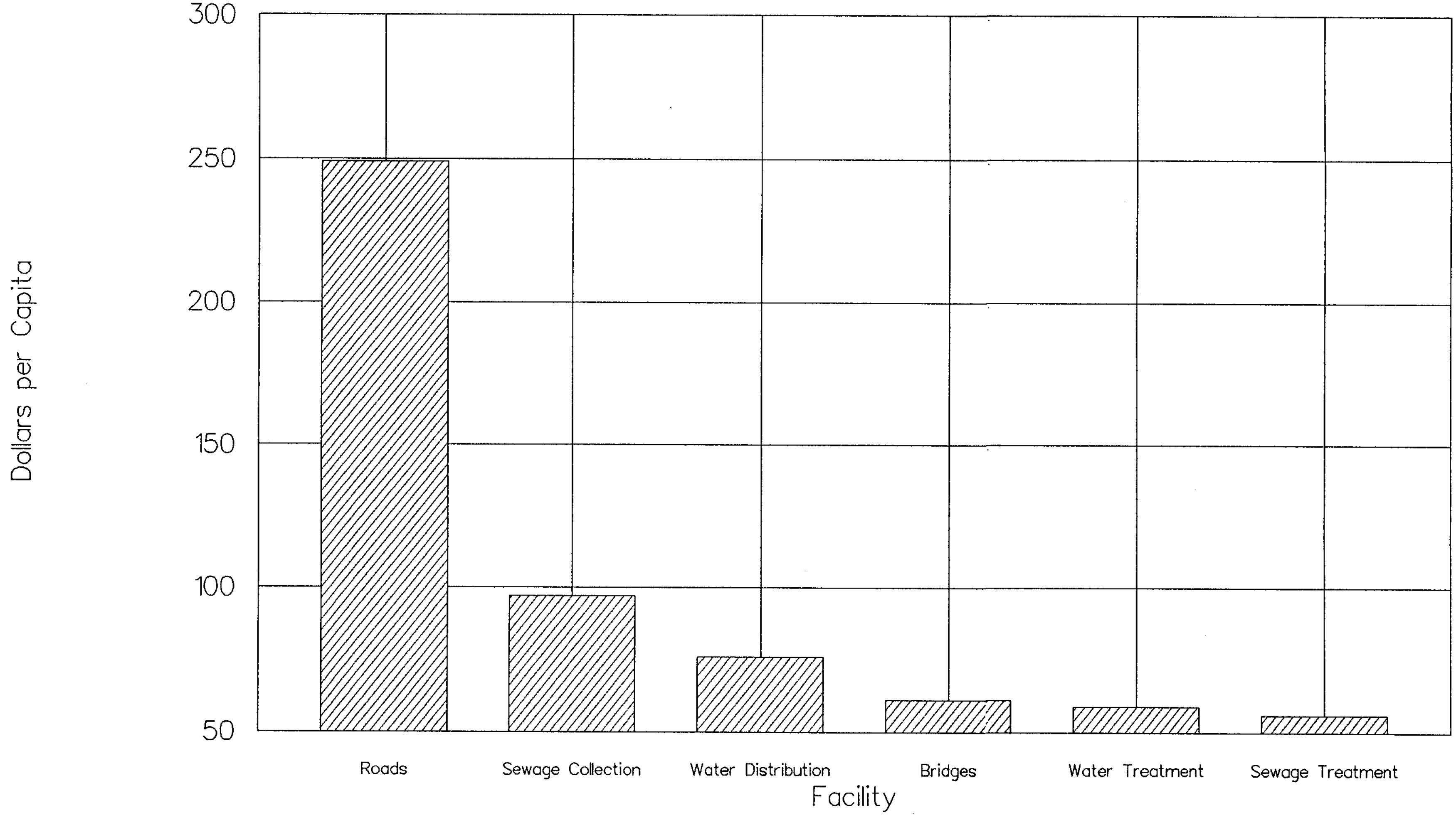
But assuming the perception is correct that the roads in Canada are in a much worse condition than the other systems, water distribution systems still represent a significant problem. Of the FCM's (1984) estimated $598 per capita (1984 dollars) required nationally to improve the six most critical physical systems, roads will require the largest share ($249 per capita or 41.7 percent), followed by sewage collection systems ($97 per capita or 16.2 percent) and then water distribution systems ($76 per capita or 12.7 percent) as can be seen in Figure 1.1. After applying inflation to the 1984 FCM figures, approximately $2.2 billion is currently required just for water distribution improvements.

1.3.2. Information and Research into Water Distribution Systems

Considering that Canadians have invested heavily in their underground systems, information and research is both sadly lacking and uncoordinated (Grover and Zussman 1985). The replacement value of the municipal water supply systems in Canada has been estimated at $62 billion, or nearly $3,000 per person served (1984 dollars), with approximately 80 percent invested in the distribution system and 20 percent in treatment (MacLaren 1985). While the large scale of this investment indicates that Canadians highly value such systems, only a small percentage of the current research in water supply is even devoted to the study of the distribution systems. In addition, while a comprehensive inventory of the water treatment facilities has been compiled by the Federation of Associations on the Canadian Environment (FACE 1987), there does not exist a comparable national inventory of the 2,887 underground systems which FACE estimated in 1986 to be serving over 21.5 million Canadians.

Research into roads rehabilitation using modern maintenance management techniques has been ongoing for the past few decades. Unfortunately, the same can not be said for the water distribution systems where techniques have not evolved dramatically in the past 50 to 60 years. Rehabilitation by cleaning and mortar lining and replacement of a deteriorated pipe with a new one by open trench methods remain the

Figure 1.1: Per capita costs by facility in Canada



Source: FCM 1984

norm. While the development of new light-weight plastic pipe materials have madeinstallation easier and more economical, procedures for improving the old pipes has come slowly. New trenchless technologies utilizing the existing "hole in the ground" have proved promising, but have not been applied extensively to pressure mains.

The American Water Works Association has in recent years compiled a guidance manual which summarizes the condition assessment and replacement management techniques developed and utilized by a few large North American utilities (AWWA 1986a). In England the Water Research Council has also been developing guidance manuals, but even with these recent developments, adequate standards and the wide-spread implementation of new techniques are slow in coming. Improvements are required in information sharing, research, and especially water rate structures aimed at proper system financing. Currently, very few communities plan for the eventual replacement of their systems by including in the price for water a charge for long-term capital requirements.

The very nature of underground systems make them especially prone to both research and funding neglect: 1) they are physically buried so their true condition can not be seen first hand by their users nor their managers; 2) they can provide satisfactory everyday service for long periods of time without having to be replaced; 3) their massive scale combined with public control means major decisions on development and funding are ultimately made at a political level. Traditionally water systems have been categorized as one of many public services, often contributing funds to general revenues, but not always getting them back when required. While the recent trends toward self-sustaining water systems through user-pay principles have been developing, competition for scarce general revenues is still ongoing for major upgrades.

When in direct competition for general revenue funding, the characteristics inherent to underground systems put them at a disadvantage. Low visibility and their mundane nature make them low political priorities; they are "out of sight, out of mind". This is made worse by a political system which demands quick, highly visible benefits over relatively short 4 or 5 year cycles, whereas the full benefits of infrastructure improvements are rarely realized in less than 25 to 50 year cycles. There are very few plaques or photo opportunities commemorating the opening of a new stretch of water main.

Part of the problem lies in modern societies emphasis on growth and things which are new and novel. Political, financial, educational, and research institutions all tend to focus on the construction, development, and eventual expansion of new works, paying little heed to the need for eventual repair or replacement of existing works. Ultimately improvement programs are more often than not crisis-driven rather than preventative (Bradley 1987, MacLaren 1987).

1.3.3. Dealing with the Physical Nature of Underground Systems

Perhaps contrary to popular belief, water distribution systems are more than simple pipes that once buried in the ground will operate for a couple hundred years with only the minimum of care needed to fix a few breaks each year. All systems eventually become inadequate over time due to either structural inadequacies or capacity inadequacies or a combination of the two (see Table 1.2).

The design life of any system depends largely on the system's purpose and may be rationally and economically determined to be quite long or relatively short. In the case of water distribution systems, the useful life is typically set anywhere from 50 to 100 years, and is often based more on the time required to pay off the system through debt financing rather than any performance criteria. Still, even with proper design, many systems develop significant problems in a considerably short period of time while others may function satisfactorily for considerably longer.

Table 1.2: Classification of infrastructure condition

	Structural	
Capacity/ Performance	Adequate	Inadequate
Adequate	A	C
Inadequate	B	D

A - does not require rehabilitation
B - requires rehabilitation for capacity inadequacy only
C - requires rehabilitation for structural inadequacy only
D - requires rehabilitation for both capacity and structural inadequacy

Source: Adams and Heinke (1987)

The design environment surrounding a water main is full of uncertainties, with many complex mechanisms which can significantly shorten its life. Corrosion, soil movement, temperature changes, and fluctuating internal and external pressures are only a few of the factors which must be accounted for in design, but which can vary considerably even over short lengths of pipe in the field. When such anomalies increase the incidence of leaks and breaks and thereby the need for repair or replacement, the result may be a serious financial burden on a community.

To manage the risks associated with pipe deterioration, some utilities formulate general repair and replacement policies, which are often based on simple criteria where a pipe is replaced when it reaches a certain age or has had a certain number of breaks. The development of such policies is often not rigorous and is largely based on broad generalizations. O'Day (1983) notes that while age may be a good indicator of the general condition of a system, it is not a useful tool in determining the need to replace an individual pipe, and Andreou and Marks (1987) note replacement based on simple break counts is much less than optimal. Thus simple replacement policies based on such generalizations cannot guarantee optimal allocation of scarce local funds.

The most effective approach being promoted in the literature seems to be one aimed at assessing the condition of the individual pipes based on performance or structural criteria, and replacing only those pipes that need it. A number of authors have developed statistical techniques for determining optimum replacement strategies based on break and repair trends (Shamir and Howard 1979, Clark et al 1982, O'Day 1983, Andreou and Marks 1987) while others have applied time-to-failure analysis and risk assessment techniques (Bratton et al 1986). However, the practical application of these techniques has been limited to mostly large utilities which generally have large staffs and many resources, and has yet to "trickle" down to the smaller centres.

Part of the reason for the slow movement of such techniques out from the larger centres is the perception that infrastructure deterioration, and more specifically water distribution system deterioration, is a big city problem and not one experienced by younger and smaller communities, which developed primarily after World War II. In reality, the problem is not limited to the older central cores of cities such as Halifax or Montreal. In Calgary, a relatively young city, a corrosive underground environment has been especially harsh on the water system. In smaller communities, which have been enduring slower growth in recent years, the average system ages are only 10 to 15 years younger than the major centres, indicating that problems first noticed in the large cities a decade ago are probably now becoming more acute in these smaller centres.

Unfortunately, many small communities lack the information, staff, and financial resources not only to deal with the problem, but to simply recognize it. Large cities such as Vancouver and Calgary have independently developed sophisticated pipe replacement models which require extensive maintenance records as well as large competent staffs specially trained in water supply. In some of the smallest communities even the most rudimentary system information has not been compiled, as-built drawings have been lost or are inaccurate and the only accurate records are in the head of a retired system operator. Staffing is also a problem in small centres, as the same person that picks up the garbage often maintains the water system (Grover and Zussman 1985).

All of these factors combine to present a picture of potentially varying levels of service among communities, less than ideal system operation and waste both in the water and financial resources.

1.3.4. Overview

While this thesis cannot come close to providing all the answers to the problem, there are a number of reasons why its approach has some merit and why water distribution system deterioration is important to look at now.

Intuitively, underground systems should be considered in the earliest stages of any general infrastructure program such as that suggested by the FCM. The reliability of the subsurface systems should be established prior to any major outlay of money directed toward the rehabilitation of surface systems such as roads and sidewalks.

Local government in Canada is currently faced with reduced levels of funding for the rehabilitation and replacement of their deficient piped water systems and while conservation and improved rate schedules promoted by the federal government over the past decade may be critical in helping to reduce the demand on such systems, they alone will not solve the entire problem, and at best can only postpone the eventual failure and repair of the piped systems.

From a national perspective, rehabilitation of water distribution systems can be considered an appropriate opportunity for local initiatives aimed at more effective resource management. Canadians are currently one of the highest per capita users of municipal domestic water in the developed world, yet pay among the lowest water rates (Tate 1990). In addition, a few water distribution systems in Canada can leak up to 30 percent of their treated water into the ground (Environment Canada 1990a). With the current concern for sustainability in our consumption conscious world, measures such as conservation, effective pricing mechanisms, leak detection, and rehabilitation / replacement strategies can all help in better managing an essential resource, our water.

CHAPTER 2: DEVELOPMENT OF CANADIAN WATER SUPPLY SYSTEMS

2.0. Introduction

A typical urban water supply system is made up of three major components: a source, a treatment and pumping facility, and a distribution system. Sources can vary from groundwater wells to surface supplies such as a lake, a large impoundment or a river. Treatment and pumping facilities vary with the type of source and the incoming water quality, but typically include surface structures which can house a number of unit processes to treat raw water and make it chemically and bacteriologically safe for human consumption. Combinations of processes can include disinfection, clarification, filtration, taste and odour control and pH adjustment, depending largely on the raw water quality and the standards being sought.

Distribution systems carry the treated water to the consumer and consist of a number of components, including transmission mains, distribution mains, storage facilities, and a variety of associated appurtenances such as valves, hydrants, and service connections.

Although this thesis concentrates on the problems associated with Canada's water distribution systems, and more specifically the "mains" in this system, it is difficult to discuss all aspects of their development in isolation from the overall water supply systems. In Canada, often the same funding programs which paid for the development of the water distribution systems also paid for the development of treatment facilities, sewers, and storm systems. In addition, some of the advances in water treatment had enormous impacts on the distribution systems, such as the development of water softening which reduced capacity losses due to the build up of deposits within pipes.

This chapter will first outline some of the general aspects related to Canadian water supply systems, the history, the funding programs, and the water quality standards, and then concentrate on some of the concerns which are more specifically related to the deterioration of the mains, such as reduced fire flows and increasing liability due to breaks.

2.1. History of Canadian Water Supply

The distribution of water through massive engineering networks is not a modern phenomena. The great aqueducts and the intricate piped systems which survived from the ancient Romans are testimony to this. In North America the development of water distribution systems may be considerably more recent, though no less impressive. In Canadian municipalities alone there are approximately 130,500 kilometres of water pipe in the ground, or enough to circle the globe 3 times. The condition, age, material type and size of this pipe is as varied as the communities it serves and the history of its installation.

This section will first describe the history of municipal water systems in Canada, outlining the rationale and extent of their development. This historical perspective is particularly important not only in setting the context for further discussion but also in the realization that many of the pipes installed in the early days of these systems are still in operation today.

2.1.1. The Early Canadian Urban Centres

Municipal waterworks and sewerage systems in Canada were developed relatively late as urban services, but were made essential by the rapid pace of urban growth (Bloomfield et al 1983). The first Canadian waterworks systems did not appear until the early 1800s, having been preceded by over 200 years of community development.

The first urban communities in Canada started as garrison points and warehouse bases for the trans Atlantic trade in fish and furs during the 17th and 18th centuries (Careless 1978). European fisherman had gathered at what is now the location of St. John's since the early 16th century, predating any other Canadian urban centre. The first major urban centres were developed by the French; Quebec City began as a staple warehouse in 1608 and by 1750 was a substantial walled city of 7,500 while Montreal was initially a mission centre to inland tribes in 1642 and with the establishment of commercial and trade functions grew to a population of 3,500 by 1750 (Careless 1978).

The British settlements followed, with a garrison centre and naval harbour established at Halifax in 1749. During the 18th century fur trade, the site of what is now Toronto was a minor post and warehouse, later to be established as York in 1793, eventually becoming the capital and military base of the new province of Upper Canada. It grew from 1,200 people in 1820 to 9,200 in 1834 when it was incorporated as the City of Toronto. Other settlements at Saint John and Kingston also emerged in the 18th century. Bytown, which began as a base for the building of the Rideau Canal, became the City of Ottawa by 1854 with a population of approximately 8,000 (Careless 1978).

The Irish migration of the 1840s and early 1850s rapidly increased the size of the eastern communities. By 1850, the population of Montreal had grown to 78,000; Quebec City to 45,000; Toronto to 31,000; Saint John to 23,000; and Halifax to 21,000 (Anderson 1988). The burgeoning growth of these centres, and the problems that accompanied it, was the main impetus behind the need to develop some type of comprehensive water supply systems.

In 1850 western Canada was still largely unsettled, but the coming of the railway in the 1880s spawned rapid growth. On the prairies, the City of Winnipeg incorporated in 1873 with a population of 1,600, growing to 25,000 by 1891. Regina first incorporated as a town in 1883 with a population of 900, followed by Calgary in 1884 with 506, and Edmonton in 1892 with 700 (Artibise 1981). Substantial growth in these communities did not come until after the turn of the century.

On the west coast, Victoria was founded by the Hudson's Bay Company in 1843, growing from a population of 4,000 in 1864 to 17,000 by 1891 (Careless 1978). Vancouver, initially laid out as Granville in 1870, incorporated as a city in 1886, one year before the arrival of the C.P.R., and by 1891 had a population of 13,000 (Careless 1978).

2.1.2. The Early Development of Water Works

There were two major factors which compelled communities to develop the first waterworks systems: protection from fire and preservation of health (Anderson 1988). Indeed, early communities were frequently plagued by conflagration as the main building material was timber. Two fires in Montreal in 1852 levelled over 1,000 buildings (Anderson 1988) while a disastrous fire in St. John's in 1892 left 11,000 people homeless (Careless 1978). Major fires also occurred in Saint John in 1877, New Westminster, B.C. in 1898, Ottawa/Hull in 1900, and Trois-Riveres in 1908 (Anderson 1988). Concern over fire protection is argued by many historians to be the prime impetus behind the eventual development of waterworks systems, with concern for public health coming much later (Anderson 1988). As J. Grove Smith wrote in 1918:

> "Apart from the importance of a public water supply from domestic, sanitary and industrial standpoints, its economic value in furnishing a ready means of controlling fires is unquestionable"

Many systems were constructed to carry water into the centre of town expressly for fire protection, and later expanded to provide domestic service only as funding permitted. In North America, the year 1652 marked the first recorded use of water pipes when wooden conduits were used to carry water from wells to storage tanks in Boston, Mass. Nearly one hundred years later, in 1746, Schaeffertown, Pennsylvania became the first community to supply all its residents with water via a piped system. But by 1800 there were still only 17 public water supplies in North America, 16 in the U.S. and one in Montreal (Grover and Zussman 1985).

The Montreal system was provided by a private company, as were many of the early systems, and consisted of wooden pipes which delivered water from springs at the back of Mount Royal to two cisterns downtown. This early system was very unreliable as the pipes frequently burst and the system was eventually abandoned. By 1816 a new firm had installed a 4" (100 mm) diameter cast iron main to bring water into downtown from a new source on the St. Lawrence River. Control of this system changed hands in the early 1820s and eventually the City took it over in 1845, extending the system through the addition of more cast iron pipes. Still the improvements to the much overworked system were inadequate, as the devastating fire of 1852 proved, and by 1856 a more efficient public system was completed (Anderson 1988).

Although Montreal had installed a marginal system as early as 1800, Saint John, N.B. is often credited with developing the first comprehensive public waterworks systems in Canada in 1837, again provided by a private company. The system brought water through a wooden duct to a steam pumping station and then through a 10" (250 mm) cast iron main to a reservoir. From the reservoir a 12" (300 mm) cast iron pipe ran to a fire hydrant at Market Square. But as with many of the early systems, it was plagued by low pressure in the cold winter months, providing only marginal fire protection. This plus the cholera epidemic of 1854 eventually forced public control of the system in 1855 (Anderson 1988).

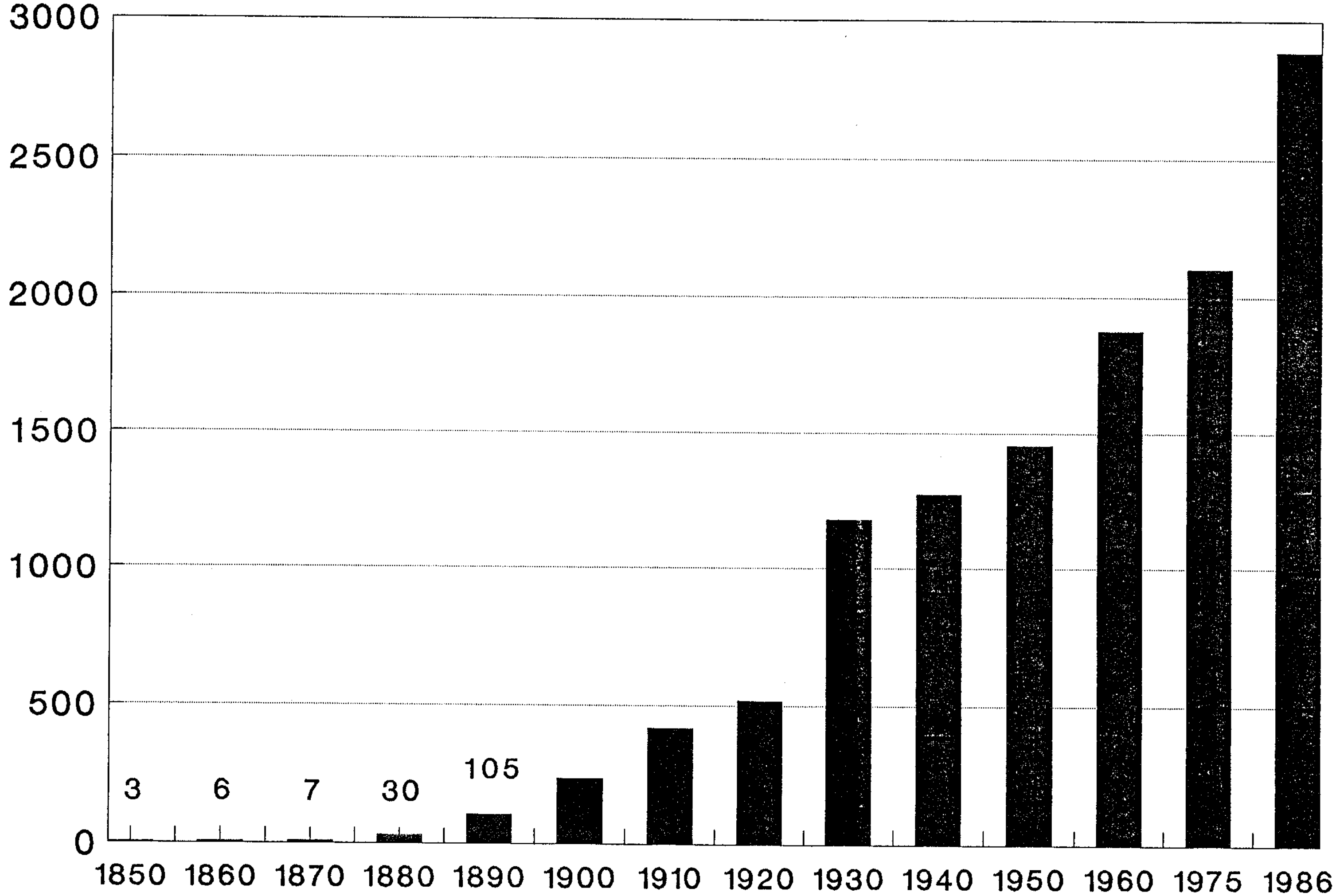
Systems followed in other eastern cities; Toronto's system was initiated in 1841; Halifax's in 1848; Kingston's in 1850; Quebec City's in 1854; and Hamilton's in 1869.

Extensive growth in the number of systems in Canada did not really occur until the 1870s. By 1850 there were only the three systems in Saint John, Toronto, and Halifax; by 1860 the addition of Montreal, Quebec City, and Kingston made six. The only system added in the decade of the 1860s was Hamilton, probably reflecting the difficulty in importing pipes, particularly cast iron during the years of the American civil war (Anderson 1988). After 1870, increasing development of water systems in the large centres became substantial enough to reduce material costs, and when combined with advances in technology, allowed system development to trickle down to the smaller communities.

Insurance companies expanded greatly between 1830 and 1880 and offered much more favourable rates to clients located in communities where the building codes forbade wooden structures and where professional fire departments and waterworks systems existed (Bloomfield et al 1981). In 1888 a member of the American Water Works Association reported that towns with waterworks could expect 20 - 30 percent rate reductions for fire insurance and by 1900, claims were made that a system could pay for itself within five years just from savings in fire loss (Anderson 1988). As can be seen in Figure 2.1, the increase in the number of systems since then has been substantial.

Fire protection remained the primary focus of water system development until the late 19th century when the suspected link between water and disease was verified. The relationship between pure water and public health, though suspected as early as the

Figure 2.1: Canada's water works
Number of systems by year



Source: M.U. 1950, 1960; FACE 1975, 1986; Anderson 1988.

1790s, was not totally understood until the discovery of bacteria in the 1880s and the uncovering of the cholera and fecal contamination link by Dr. John Snow following a cholera epidemic in London which claimed 250,000 lives between 1845 and 1849 (Grover and Zussman 1985, Anderson 1988). This discovery displaced the earlier "miasmatic" theory of disease which attributed disease to filthy urban conditions; miasma being the poisonous atmosphere that can arise from swamps, marshes, urban gutters and streets (Baldwin 1988). In the 1850s, Dr. Snow's new "contagion" or "germ" theory of disease spawned the argument that a pure system of water must be paralleled by a separate system dedicated to the disposal of human and industrial wastes (Bloomfield et al 1981).

Even after the implementation of sewage collection works, many Canadian cities were still ravaged by typhoid and cholera epidemics throughout the 19th century and into the 20th, as the early water systems had no means of disinfection. The problem was worsened by the fact that many communities used common waters for both consumption and sewage disposal, such as Toronto on Lake Ontario.

Treatment was to solve this problem. Some of the rudimentary techniques of water treatment such as simple sedimentation were known by ancient cultures which discovered that some solids can be removed from turbid water if the water is allowed to sit undisturbed. The first modern attempts at treatment began with filtration, with the first plant being built in Paisley, Scotland in 1804, with similar systems constructed in Paris in 1806, London in 1829 and finally in North America in Poughkeepsie, New York in 1871. Early attempts at filtration in Canada at Kingston in 1849 and Hamilton in 1859 were less than successful, and the first operational treatment plant in Canada was Jinks Filter in Fredericton in 1891 (Grover and Zussman 1985).

Probably the most effective means of treatment for disinfection was by chlorine, which was found to destroy a wide range of pathogenic bacteria. The first large scale use of chlorine was in Middlekerke, Belgium in 1902 and the technology was rapidly adapted after its first use in North America in Jersey City, New Jersey in 1908.

In 1909, Toronto completed the construction of its sewage outfall on Lake Ontario, 7 kilometres from the City's water intake, a separation thought to be more than adequate considering that the predominant lake currents were in a direction which should have carried the sewage away from the water intake. But the typhoid fever epidemic of 1910 proved this wrong, and the city was forced to provide chlorination of its water. The effects of treatment were significant, reducing the death rate from 44 down to 22 per 100,000 almost immediately, and by half again after completion of a filtration plant in 1912 (Anderson 1988). By 1918 the rate was down to only 0.9 deaths per 100,000 (Grover and Zussman 1985). Montreal implemented chlorination in 1910 following a similar typhoid outbreak with results similar to those in Toronto and the future of such treatment in Canada was sealed.

Other Canadian cities followed the early leads of Toronto and Montreal in water treatment, with Fredericton installing a rapid sand filter in 1906 and chlorination in 1931. But even with these convincing reductions in water-borne diseases, some communities resisted treatment, priding themselves on the purity of their water and perceiving treatment as an unnecessary evil. In Vancouver during World War II the U.S. Navy was contracting for port facilities and insisted on chlorinated water. Dr. E. A. Cleveland, in charge of metropolitan Vancouver's water system at the time, resisted pressure from the federal government to chlorinate, claiming "No case of disease has ever been traced to this city's water supply." It was only after much public debate and political pressure that Vancouver eventually did introduce chlorination, and maintains it today (Cain 1976).

Even so, not all communities in Canada have, nor require, treatment facilities to maintain their water quality standards. In 1987, FACE surveyed the water and sewer systems in 3,650 municipalities with a total population of 22,032,162; representing about 88 percent of the national population, with the remaining 12 percent being largely rural and for the most part served by private supplies. The survey shows that only 57 percent of the communities surveyed maintain water treatment facilities, though they represent 89 percent of the surveyed population, while 89 percent of the communities have water distribution systems, serving 97 percent of the total surveyed population. These numbers imply that the majority of communities without water treatment are very small, with many of them located in Quebec, New Brunswick and Prince Edward Island, though most still have some type of shared distribution system (see Table 2.1).

Table 2.1: Water supply services in surveyed Canadian communities in 1986

	Percentage of Communities Surveyed with Distribution Systems	Percentage of Communities Surveyed with Treatment Plants	Percentage of Population Surveyed with Distribution Systems	Percentage of Population Surveyed with Treatment Plants
B.C.	93	61	100	85
Alberta	89	77	100	99
Saskatchewan	94	92	100	97
Manitoba	70	60	97	94
Ontario	96	86	100	90
Quebec	69	36	94	87
New Brunswick	74	24	89	62
Nova Scotia	79	68	95	93
P.E.I.	38	4	82	36
Newfoundland	77	64	93	76
N.W.T.	100	96	100	94
Yukon	100	73	100	83
CANADA	**79**	**57**	**97**	**89**

Source: Adapted from FACE (1987)

On a regional basis, the degree of treatment among Canadian municipalities is quite variable. For instance, approximately 60 percent of the communities in B.C. and Manitoba are served by water treatment, but as can be seen in the first two columns of Table 2.2, the average number of unit processes required for treatment in Manitoba is 2 1/2 times that of B.C. In B.C. most water treatment plants only carry out disinfection with a few carrying out clarification. By comparison, in Manitoba most plants carry out disinfection, clarification, chemical removal, and some pH control.

Table 2.2: The extent of unit treatment processes in Canada in 1986

	Avg. Unit Processes per Community Surveyed	Avg. Unit Processes per Treatment Plant	Avg. Unit Processes per Treatment Plant by Type					
			Disinfection	Clarification	Removal	pH Control	Fluoride	Other
B.C.	0.9	1.4	1.0	0.2			0.2	
Alberta	2.2	2.8	0.9	1.1	0.5	0.2	0.2	
Saskatchewan	3.8	4.1	1.0	1.3	1.2	0.1	0.4	0.1
Manitoba	2.1	3.5	1.0	1.2	0.7	0.1	0.2	0.1
Ontario	2.3	2.7	1.1	0.9	0.2	0.1	0.2	0.2
Quebec	0.7	1.9	0.8	0.7	0.1	0.2	0.1	0.1
New Brunswick	0.4	1.7	1.0	0.4	0.1	0.1		
Nova Scotia	1.4	2.1	0.9	0.5	0.1	0.4	0.2	
P.E.I.	0.1	2.0	1.0				1.0	
Newfoundland	0.7	1.1	1.0	0.1				
N.W.T.	1.4	1.4	1.1	0.2			0.1	0.1
Yukon	0.9	1.3	1.1				0.2	
CANADA	**1.4**	**2.4**	**0.9**	**0.8**	**0.3**	**0.1**	**0.2**	**0.1**

Notes:

"Disinfection" can be by chlorine gas, chlorine compounds, and/or ozone.
"Clarification" can include filtration, sedimentation, coagulation, and/or carbon absorption.
"Removal" can include aeration, iron and manganese removal, softening, and/or taste and odour control.

Source: Adapted from FACE (1987)

In general, the most intensive treatment is carried out on the Prairies, where ground water supplies contain high levels of dissolved minerals and where surface supplies are frequently contaminated by runoff across silty, organic soils. The least intensive treatment is in the Atlantic provinces, in Quebec, and in B.C., where the quality of supply is good.

But water treatment is not the only means of maintaining water quality. Some of Canada's largest urban centres maintain restricted access to watersheds and require only minimal treatment of their potable water; for instance, the cities of Victoria, Vancouver, Winnipeg, and Saint John still rely on impounded surface supplies to provide quality raw water, with chlorination the only additional treatment performed (MacLaren 1985).

2.1.3. The Push for Publicly Owned Utilities

The provision of domestic water has historically been a municipal responsibility, versus a regional, provincial, or federal one. The earliest systems in North America were provided by private companies, but by the early 20th century there emerged a trend toward municipal take-overs of many of the privately owned systems.

A number of factors led to this trend. It was becoming very difficult for private companies to operate profitable operations while at the same time providing the level of service required by the expanding demands of both fire protection and domestic use. In addition, these companies were not compelled by law to provide either service and often delayed action until forced by some crisis such as fire or an epidemic (Bloomfield et al 1981).

A general "public ownership" movement was another factor influencing the shift to municipal control of utilities. Supported by a powerful rhetoric, the movement had initially gained appeal in the 1890s claiming that "municipal socialism" would be far cheaper and more efficient than private enterprise, citing successful models in Britain and elsewhere (Bloomfield et al 1981).

In 1882 privately controlled waterworks systems out-numbered the municipally controlled systems and the government of Ontario passed legislation to guide in the granting of new franchises to private companies. But by the turn of the century, over 50 percent of Ontario's water systems were municipally initiated, while another 19 private waterworks had been taken over by municipalities. By 1950, 52 municipal takeovers had been recorded leaving very few private waterworks companies in Ontario (Bloomfield et al 1981).

Although supporting the same types of controls as the "public ownership" movement, another movement in western Canada based its arguments on the opposite end of the ideological spectrum. In the early 1910s, municipal ownership of utilities was compelled by the business community and its desire to keep input costs as low as possible. At the time, a University of Toronto political economist determined that privately owned utilities charged up to 50 percent more than publicly owned waterworks systems for the same level of service (Anderson 1979). In Winnipeg and other cities, the desire for more "business-like efficiency" in the operation of the utilities was directly related to plans for the restructuring of local government which incorporated many features of private business corporations (Anderson 1979).

Regardless of the impetus, once a municipality had taken over control of a water system, it almost invariably undertook a major expansion of service, improving both the quality and reliability of the systems.

The results of all these early efforts to privatize and expand can be seen today. Of the 2,923 water treatment plant operating authorities across Canada in 1986, only 200 were private, 213 were provincial, and 2,510 were municipal (FACE 1987). Of the private authorities, most were in Quebec (185), and the remainder were in

Newfoundland (7), Manitoba (4), Nova Scotia (2), B.C. (1), and the N.W.T. (1).

Today many of the larger Canadian systems have now expanded to provide water to vast surrounding regions. In the metropolitan areas of both Vancouver and Toronto for example, regional authorities deliver treated water to a number of individual municipal distribution networks which in total serve 1.5 million and 2.5 million people respectively.

2.2. Funding for Water Systems

The FCM (1984) report on the physical condition and funding adequacy of Canada's Urban Infrastructure paints a picture of dwindling funds from higher levels of government in the provision of physical infrastructure. Funding shortfalls were ranked as the number one impediment to infrastructure renewal in the 1984 FCM survey, with inadequate staffing levels a close second, especially in the smaller communities surveyed. Except for the most recent change in policy by the federal government in the last few months, the situation had not improved drastically over the past decade.

The policy of the federal government had been to move away from massive injections of federal funds to solve local problems and to move toward improvements in local "user-pay" financing by offering technical support. Access to federal funding for actual water and sewer system improvements would only exist for projects that meet the objectives of other federal programs such as economic development and job training (Environment Canada 1987, Environment Canada 1990b). The main reasons behind this shift was the view that federal funding combined with local "flat rate" pricing schemes subsidize water systems to a point where water is artificially under-valued and over-used by the consumer, thereby causing wastage and system over-design (Tate 1990).

Although federal funding has never risen to cover more than 35 percent of the total capital costs of water and sewer development in any given year, the withdrawal of these funds over the past decade has nevertheless resulted in a net funding shortfall for local works. Diminishing federal funds have been paralleled by slow or negligible changes in local funding and slowly declining or relatively constant funding levels from the provinces. The impact of federal government funding on construction, which peaked in the late 1970s can be seen in Table 2.3 and Figure 2.2.

Table 2.3: Total value of construction work on water distribution systems in Canada 1973 - 1983

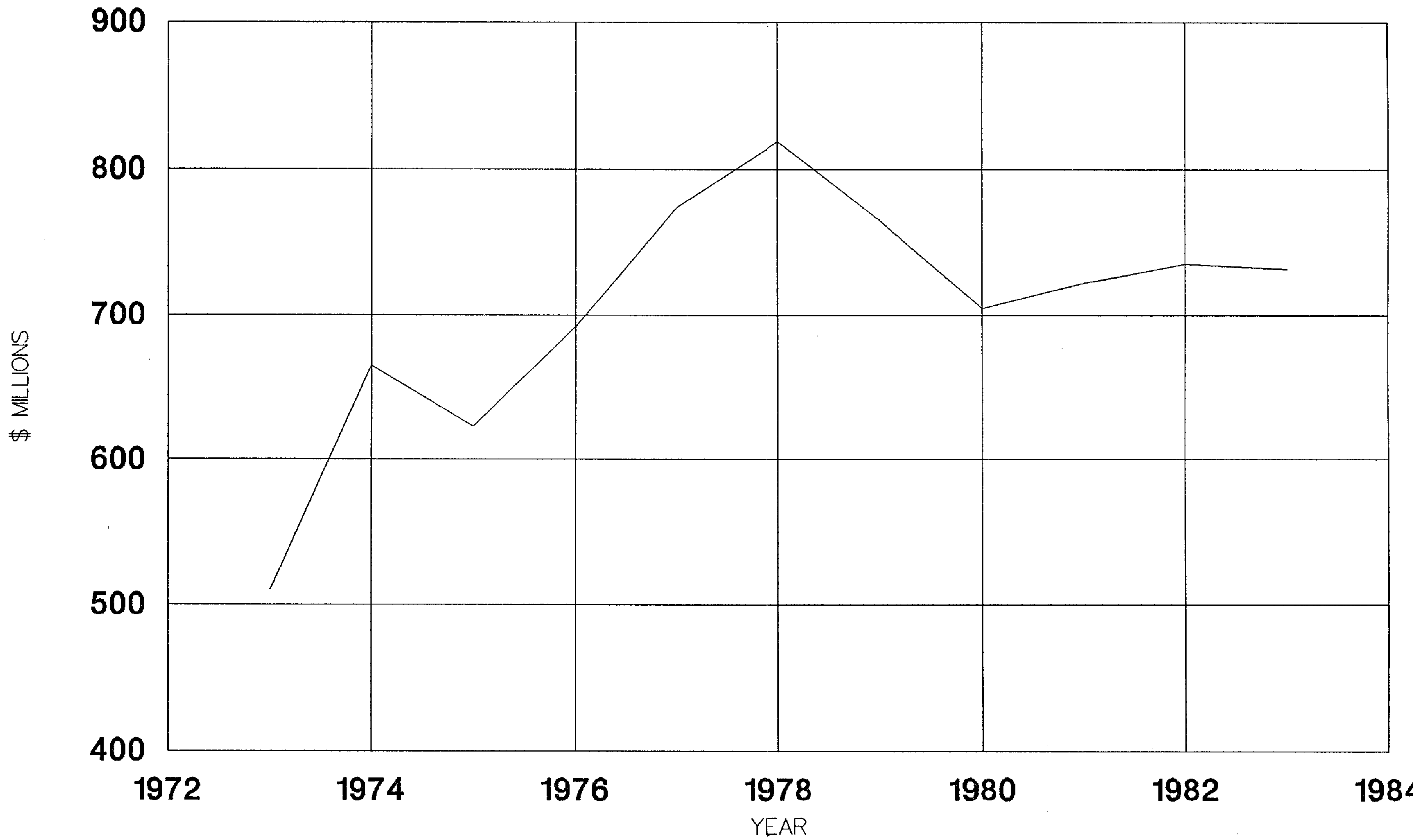
DATE	WATER MAINS, HYDRANTS, AND SERVICES ($ millions)	
Current Year	Current Prices	1983 Prices
1973	199	510
1974	299	665
1975	311	623
1976	380	692
1977	439	774
1978	516	819 (Peak)
1979	528	765
1980	543	705
1981	606	722
1982	684	735
1983	732	

Notes: 1) data includes repairs as well as new construction.
2) 1983 prices based on Energy, Mines and Resources Canada index.

Source: Grover and Zussman (1985)

Due to the reduced spending, capital works have been deferred and the backlog is now at the point where it merits a review of the involvement both the past and the present players have had in infrastructure development.

Figure 2.2: Total value of construction work on Canadian water distribution systems



Amborski and Slack (1987) outline the historical and current roles of the three levels of government - municipal, provincial, and federal - which have been involved in the financing of urban infrastructure. After World War II, funding for public works was kept up to date by the post-war development boom and the need for new facilities brought on by a burgeoning population (FCM 1984, Amborski and Slack 1987). All three levels of government were very involved in the financing of infrastructure up until the end of the 1970s, but a combination of factors have contributed to the decline since then (FCM 1984):

1) higher inflation in the 1970s meant higher taxes and increased construction costs,

2) governments provided an increasing array of services to improve the quality of life thereby increasing the burden on the tax payer and increased competition for funds,

3) interest rates soared in the early 1980s, reducing the capacity and desire of local government to fund through debt financing,

4) community and environmental concerns often made the political climate difficult, and

5) government restraint was introduced to reduce the deficit.

These factors have all contributed to a slow, though steady, deterioration in facilities and a lack of an effective strategy to deal with it.

Currently the funding to finance water treatment and distribution systems comes from two major sources:

1) recurring revenues such as from user charges (tariffs) and municipal taxes, and

2) local sources of capital, such as bond issues and grants from developers, or from provincial sources, through loans and grants.

Operation and maintenance budgets come largely from the first source (Curtis 1991a), while a good share of capital cost financing comes from the second (Grover and

Zussman 1985). The FCM survey (1984) notes that most funding for operation, replacement, and rehabilitation comes from local user fees which provide 86 percent of the funding for water distribution systems and 83 percent for water treatment.

For the past decade, prior to the recent federal election, local government has lobbied to get the higher levels of government, especially at the federal level, re-involved in funding. Amborski and Slack (1987) outline three basic rationales which are typically used to justify involvement beyond the local level:

1) spillover,

2) fiscal equity, and

3) the national character of urban infrastructure.

Generally spillover is the strongest of the three and includes financing local works where the costs and benefits of the works "spill over" to other jurisdictions. The level of assistance is usually proportional to the benefits which will be felt outside the jurisdiction. Unfortunately, in the case of water distribution systems, the spillover rationale is not easily applied. Unlike road systems which can connect to form vast inter-jurisdictional networks or sewage treatment plants which can protect downstream users from pollution, most of the costs and benefits of water distribution systems are contained within the municipality.

Fiscal equity includes funding assistance to municipalities which would otherwise have to bear unduly high tax rates in order to maintain some national or provincial level of service. This is more applicable to water distribution, especially at the provincial level since the maintenance of water quality and distribution standards is constitutionally a provincial concern.

The final rationale applies more at the federal level and uses the argument that infrastructure forms the backbone of the national economy. Although a popular argument, in many ways it is too generic. From the federal perspective, many other functions in our society also contribute indirectly to our national productivity, yet still remain outside the immediate jurisdiction of the federal government and direct federal support.

2.2.1. Federal Programs

Historically, federal programs aimed at the provision of water distribution systems, and infrastructure in general, have neither been constant over time nor consistent in purpose. There does not exist a precedent to fund infrastructure exclusively for the purpose of rehabilitation and the position of the federal government through the 1980s was that is did not want to set one. While the federal Liberals now in power have introduced a new infrastructure program, previous federal programs have contributed to the development of Canadian systems.

It has been suggested that large scale investment in infrastructure by the federal government was initiated in response to the economic depression of the 1930s (Environment Canada 1975). Many municipalities and several provinces, as well as the country as a whole, were experiencing severe economic problems when Canada, following the lead of the United States, provided funds for large public works projects to create jobs and stimulate the economy in the late 1930s. But such involvement was short lived and despite massive urbanization immediately following World War II, the federal government largely ignored the area of water supply and wastewater funding. However, concern regarding the pollution of the Great Lakes in the early 1950s again prompted federal involvement and legislation was eventually passed which allowed for the implementation of programs to improve water supply treatment and wastewater systems (MacLaren 1985).

Although the federal government has supplied billions of dollars to aid local authorities in the provision of their public systems, nowhere can be found a complete record of these programs, their objectives, the actual expenditures and the results achieved (Grover and Zussman 1985). MacLaren (1985) notes that between 1961 and 1980 the Central Mortgage and Housing Corporation (CMHC) contributed considerable capital to the assembly and servicing of raw land for urban expansion, yet the value of this capital is not readily forthcoming but is known to be considerable with respect to local water, sewerage, and drainage facilities. Still, a partial listing of the major federal programs and the corresponding funding is important to illustrate the nature of federal involvement.

There were four major national programs which contributed in some part to the development of Canadian water supply systems between 1961 and 1980:

1) Municipal Infrastructure Program (1961-1978)

2) Neighbourhood Improvement Program (1974-1977)

3) Municipal Incentive Program (1975-1978)

4) Community Services Contribution Program (1979-1980)

All four of the programs involved contributions made by the federal government through the CMHC.

The Municipal Infrastructure Program contributed a total of $2.5 billion between 1961 and 1978, with $500 million as grants and $2 billion as loans (Grover and Zussman 1985). The first 14 years of the program focused strictly on sewage treatment, but from 1975 to 1978 funding was also provided to build new water works systems in areas that were previously unserved. The portion of the total funding which was applicable to both water works and sewerage systems between 1975 and 1978 was $1.4 billion, with $395 million as grants and $1 billion as loans. This program remains the historical peak in federal funding and at the time represented 35 percent of all capital expenditures on water supply and sewerage in Canada (Grover and Zussman 1985).

The Neighbourhood Improvement Program was implemented in 1974 as an amendment to the National Housing Act. It authorized CMHC to enter into an agreement with a province to assist a municipality for up to 50 percent the cost of a number of items related to neighbourhood improvement developments, such as formulating plans and acquiring land, and up to 25 percent of the cost of improving municipal and public utility services. The federal commitment over the life of the program was $199.5 million, with additional contributions from the provinces of $108 million and from the municipalities of $184 million. The program was terminated in 1978 in favour of the Community Services Contribution Program (MacLaren 1985).

The Municipal Incentives Grants Program was instituted in November 1975 as an amendment to the National Housing Act. The program was implemented to encourage the development of medium density housing in Canada by permitting CMHC to contribute $1,000 to a municipality for each eligible housing unit constructed within its boundaries, given the units were connected to municipal services and that certain density limitations were met. The program operated on a total federal contribution of $128 million and was terminated in 1978, again in favour of the Community Services Contribution Program (MacLaren 1985).

The Community Services Contribution Program replaced the three previous programs under the National Housing Act and authorized the CMHC to enter into agreements with the provinces in order to reimburse the expenditures of municipal improvements as set out in the agreement. The program was designed to be more responsive to the needs of local municipalities, while at the same time shifting administrative responsibilities over to the respective provinces. Each province received funds as calculated by a formula based on its urban population and municipal taxes. The program lasted two years, with $150 million allocated in 1979 and $250 million in 1980. Although it financed 10 percent of the national expenditures on water and sewer services at the time, these were not the only community services eligible for funds; a few of the others included neighbourhood conservation and the provision or improvement of social, cultural, and recreational facilities (MacLaren 1985).

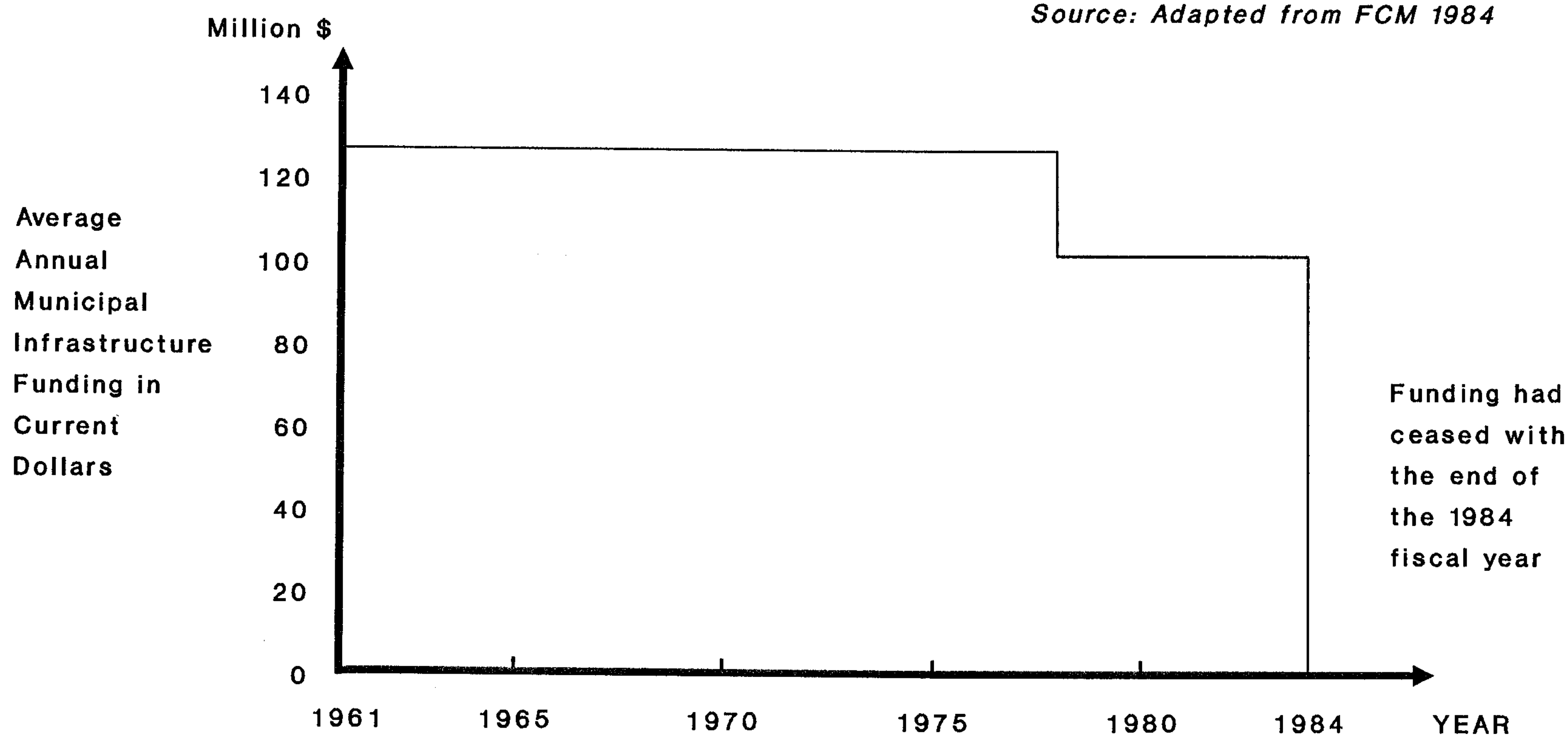
By the early 1980s, all these nation-wide programs which assisted in the development of water supply systems had ceased. Figure 2.3 shows the tremendous impact of the federal government's withdrawal of support, and provides some insight into the current funding crisis. The main reasons given by the federal government for the withdrawal included the desire to hold down the deficit, the consideration that the federal government should discontinue funding services that were the jurisdiction of the provinces and their municipalities, and the determination that job creation money could be better spent elsewhere (MacLaren 1985).

There have been and still are a number of smaller federal programs which provide funding for water and/or sewer works. The federal government conducted a Winter Works Subsidy Program through Public Works Canada in the mid 1960s to encourage winter work on municipal works, including water and sewer, thereby reducing unemployment during the colder period of the year.

In 1968 the Department of Regional Economic Expansion initiated a program of

Figure 2.3: Average levels of federal infrastructure funding

Source: Adapted from FCM 1984



Included are the following programs:

1) Muncipal Infrastructure Program (1961-1978)	$ 2	Billion
2) Neighbourhood Improvement Program (1974-1977)	$199.5	Million
3) Municipal Incentive Program (1975-1978)	$128	Million
4) Community Services Contribution Program (1979-1980)	$400	Million
5) Urban Transportation Assistance Program (1978-1984)	$230	Million

grants and loans to assist municipalities through their provinces with the expansion and improvement of their infrastructure including water and sewer systems. General Development Agreements with the provinces were responsible for the expansion of the water distribution system in Saint John, N.B. and advanced water treatment in Regina (MacLaren 1985). The Prairie Farm Rehabilitation Administration has been responsible for the development of rural water systems in the prairie provinces, supplying technical support as well as funding through grants and loans to small communities.

A number of other departments within the federal government also provided funding. Environment Canada in 1983 provided $9.5 million to various communities for water and sewer plants, while the Department of Indian and Northern Affairs provides the infrastructure on Indian reservations (Grover and Zussman 1985).

While all the federal programs outlined were aimed at providing money exclusively for new capital works, the new program recently introduced by the federal Liberal government will include the rehabilitation of existing works. A report prepared by the Lands Directorate of Environment Canada (Birchan and Bond 1984) suggests that funding programs undertaken by the federal government should give preference to servicing land for infill, redevelopment, or revitalization where choices exist and require communities to follow plans which support compact development.

The Federal Water Policy (Environment Canada 1987) outlines the federal government's position throughout the 1980s and early 1990s on matters concerned with the provision of water supply systems. The policy suggests that municipal water in Canada is currently under-valued and, in order to allow Canadians to fully realize the value of this scarce resource, is supporting pricing schemes based on the philosophy of "user-pay". The means with which to achieve this are through demand management and metering (Tate 1990), and a reduction in direct funding which tends to over-subsidize (Environment Canada 1990b).

The former federal government reiterated its lack of interest in funding any large scale rehabilitation programs despite calls from the FCM for a cost shared 1/3 - 1/3 - 1/3 federal, provincial, municipal program. According to the FCM, the capital requirements of all forms of infrastructure, if spread out over the next ten years with costs borne entirely by the local government, would result in a 7 percent increase in total municipal budgets. The cost shared program proposed by the FCM and now adopted by the new federal government could reduce the local budget increase to only 2 to 3 percent (Curtis 1987).

The new found support of the federal government suggests agreement with the FCM's view that federal involvement can be justified when new federal legislation is passed which directly requires the upgrading of existing facilities (Curtis 1991b). In the U.S. for example, the federal government has provided some financial assistance for necessary improvements following the passage of stricter environmental legislation. The current political position of the FCM expressed by its political Task Force on Infrastructure is to continue pressuring senior governments for funding, even though municipal governments have generally not provided their one-third share (FCM 1991b).

Although the details of the new two year $2 billion federal program, with equal contributions by the provincial and local bodies, would amount to a total national program of $6 billion, the details of the program have yet to be announced as to the extent of funding for water distribution systems. It is known that the program will include roads and public buildings, meaning the share of funding for water distribution systems will be only a fraction of the total amount. While this funding program is unprecedented, at least over the past decade, it is only a $6 billion start to solving what may be a $30 billion problem and, undeniably, from the federal perspective much of the reasoning behind the program is job creation rather than effective infrastructure improvement.

2.2.2. Provincial Programs

Provincial grants and funding programs have also played a major role in the development of water systems. Theoretically the ability of provincial governments to provide funding for infrastructure is quite large. Local municipalities often receive unconditional grants from the provinces which may be used for the provision of municipal infrastructure, with the decision of where to spend being a local one. But since these unconditional grants have not generally increased over the years, there are few funds to transfer to infrastructure rehabilitation. In addition, over the past twenty years local governments have chosen to fund more politically advantageous social programs rather than the necessary, though less prominent, infrastructure requirements. So even with the presence of unconditional funding there is little guarantee it will be directed toward rehabilitation (Grover and Zussman 1985).

Conditional grants to local governments aimed at infrastructure provision vary from province to province, but in general still represent only about 2 percent of total revenues for water supply and 18 to 19 percent for roads and bridges (Amborski and Slack 1987). So for now, in most provinces, the decision to fund water distribution rehabilitation remains exclusively a local responsibility.

The most recent movement toward full fledged rehabilitation funding from a provincial level has occurred in Ontario and Alberta. Following the initial survey by the

FCM in 1984, most provinces embarked on similar surveys to include those communities which were missed in the national survey and thereby allow a better assessment of their general infrastructure (Curtis 1991a). But both Ontario (McIntyre and Elstad 1987) and Alberta (Grover 1990) have gone one step further and completed even more detailed province-wide age and condition surveys of their underground utilities, with the intention of developing programs to encourage the rehabilitation of water main and sewer infrastructure.

In Ontario, the initial age and condition survey has been followed up by a 50 percent municipal / 50 percent provincial cost shared "needs studies" program to allow individual municipalities to identify their specific needs and appropriate courses of action should an actual rehabilitation construction program be implemented (McIntyre and Elstad 1987). To date approximately 200 of the province's 430 water systems have completed the needs studies (MacLaren 1991). The framework for the rehabilitation program was outlined in 1983 for the Ministry of Environment (MacLaren 1983), but to date a full-fledged funding program has not materialized.

In Alberta, funding programs which allow for infrastructure rehabilitation have already been approved. The Alberta Department of Municipal Affairs has implemented two unconditional grant programs to Alberta municipalities which may be used for infrastructure upgrading. The Alberta Municipal Partnership in Local Employment (AMPLE) program which started in 1987 is providing $500 million in unconditional grants over a 7 or 8 year period to local government. The second program is the Alberta Partnership Transfer (APT) program which in 1988 combined previously individual payments for municipal assistance into a single unconditional grant and is providing approximately $150 million per year (Grover 1990).

Alberta has also expanded the availability of its conditional provincial capital grants to include not only new construction, but infrastructure rebuilding as well. These grants are administered on a 25 percent municipal and 75 percent provincial cost sharing basis. The Alberta Municipal Water Supply and Sewage Treatment Assistance Programs administered by the Department of Transportation and Utilities provided $40 million in 1988/89 and $35 million in 1989/90 (Grover 1990).

The programs implemented by Alberta represent the first move in Canada toward a bilateral provincial-municipal funding model which has become common in the U.S. where a variety of states are implementing similar bilateral programs rather than waiting for federal involvement. Some of the states involved include California, Washington, New Jersey, Connecticut, Oregon, Georgia, New Mexico, Massachusetts, and Ohio (Curtis 1991b).

2.2.3. Local Programs

As outlined previously, the bulk of funding for water distribution rehabilitation now comes from local user-fees, with smaller amounts coming from capital works budgets that draw upon unconditional provincial grants or general revenues.

In general, maintenance programs in Canada are not underfunded to the extent that capital works are (Curtis 1991a). But the backlog in capital works does imply that maintenance dollars are probably not being spent as effectively as intended, and are often being used to hold together systems which, from an economic point of view, should have been replaced or rehabilitated years ago.

"User-fees", which in the case of water supply are administered through water rate schedules, are a double edged sword to municipalities. On the one hand, they provide direct funding for systems thereby allowing local autonomy and less reliance on higher levels of government; theoretically, they are easy to change as demand requires. But on the other hand, the reality of the political process, the mood against any increased taxes or fees for municipal services, and a competitive marketplace dictates that user-fees, as with local tax rates, must be kept as low as possible both to attract new residents and industry and to keep the existing ones happy. The reluctance among local governments to increases water rates is evident in the fact that, while water systems are in better condition than say roads which are not funded by direct fees, there still remains a multi-billion dollar funding shortfall in water systems.

Tate (1990) suggests that the extremely low municipal water rates in Canada do not reflect the true value of our water resource nor the huge investments made in our water systems. As can be seen in Tables 2.4 and 2.5, Canadian drinking water is indeed cheap.

Tate argues that these unrealistically low prices invite problems. The inverse relation between price and water demand is well documented by Howe and Linaweaver (1967), Grima (1972), and Hanke (1978), from which Tate concludes that the under-valuing of treated water leads to increased wastage, inflated demand, and the ensuing over-design of treatment and distribution facilities.

The total cost an individual consumer pays for water service depends on both the water rate and the rate structure itself. There are two main types of water rate structures: volume charges, which require metering of each consumer, and flat rates which do not. Both rate types possess characteristics which can either promote or discourage excessive water demand.

Table 2.4: Comparison of average international water prices in 1986

Country	Price ($/1000L)
Australia	1.65
Germany	.99
France	.75
Belgium	.70
United States	.53
United Kingdom	.50
Sweden	.50
Canada	.25
Italy	.17

Note: does not include the cost of waste treatment; in Canada this would raise the price to $0.47.

Source: Tate 1990

Table 2.5: Typical prices for popular liquids

Liquids	Cost ($/1000L)
Beverages	
Tap Water	0.47
Cola	787.00
Milk	900.00
Perrier Water	1,333.00
Beer	2,000.00
Wine	6,000.00
Whisky	18,000.00
Gasoline	550.00

Note: Tap Water price based on the average Canadian monthly residential water price for 35,000 Litres.

Source: Tate 1990

A 1986 survey of 470 municipalities by the federal government reveals that, of the 1,110 rate schedules submitted, over 70 percent are such that they do not discourage excessive water demand (Tate 1989).

2.3. Legislation

While legislation in the general field of water is extensive, with 15 major water related pieces of federal legislation and 82 pieces of provincial legislation estimated in 1985 (Grover and Zussman 1985), the legislation governing municipal water distribution systems is limited.

2.3.1. Federal

Federal legislation impacting water distribution systems is almost non-existent. Federal involvement in the broad area of water is derived from the powers outlined in the 1982 Constitution related to navigation and shipping (s.91 [10]), seacoast and inland fisheries (s.91 [12]), and criminal law (s.91 [27]). On a broad basis, the federal government also maintains the right to pass legislation for the peace, order, and good government of Canada.

The majority of federal water legislation is aimed at the protection of receiving waters. For instance the Fisheries Act allows for compensation of fisherman whose livelihoods may be affected by pollution deleterious to the health of the fish resource. The Pest Control Act deals with the control of pesticides especially related to the contamination of groundwater. The Clean Water Act is designed to allow cooperation with the provinces in managing water resources on a nation-wide basis, allowing for nation-wide information gathering and scientific transfers. The Environmental

Contaminants Act protects human health and the environment from substances that could potentially be harmful and is meant to be used as residual legislation where other provincial or federal legislation may come up short.

Probably the most significant federal function is not related to legislation or regulation, but rather entails the continuing development of drinking water quality guidelines. These guidelines are not currently enforceable through federal law, as water quality is a responsibility of the provinces, but most provinces have adopted the guidelines with some provinces maintaining additional standards for locally significant water contaminants.

The first federal water quality standards were instituted in 1923 to regulate the bacteriological quality of water on ships in the Great Lakes. In 1968 the first national drinking water guidelines were developed through the cooperative efforts of the federal and provincial governments as well as the Canadian Public Health Association (Morrison 1984). These initial guidelines covered certain microbial and physical characteristics, radio nuclides, and some inorganic and organic chemicals. Since then, improvements in analytical chemistry resulting from the development of gas chromatographs and mass spectrometers have increased detection capabilities to parts per billion and even quadrillion (Mannion 1988). This, as well as increased information on the safety of substances, has resulted in updates of the guidelines in 1978, 1987, and 1989 (Health and Welfare Canada 1989).

2.3.2. Provincial Legislation

The rapid developments in the medical field of the 1850s compelled provincial governments to enact the first legislation which ensured the proper development of water systems. Provincial boards of health were created in Ontario in 1882 and in Quebec and New Brunswick in 1887. Although their powers were initially advisory, in Ontario and Quebec they were expanded such that all plans for water and sewer systems had to be approved (Anderson 1988).

Today, the Canadian Constitution of 1982 gives a province nearly exclusive control over its water resource (Grover and Zussman 1985). With respect to water supply systems, a province typically delegates some of this control to a municipal corporation through some form of enabling legislation (ie. a Municipal Act or a Public Utilities Act). Such legislation empowers a municipality to acquire, establish, and operate water works for the supply of drinking water to its inhabitants. The power is often a permissive one, but most municipalities have undertaken to supply this public utility (Wood 1987).

The province usually reserves the right to regulate water quality and to control general design and construction standards. Among the provinces in Canada there is a wide array of legislative and persuasive methods of controlling drinking water quality, but as of 1985 only Quebec had entrenched in its legislation enforceable rules governing the quality of drinking water. Assuming this remains the case today, outside of Quebec a person would have no legal recourse against a water supply utility which is providing lower quality water than specified in the national guidelines (Grover and Zussman 1985), that is, unless it can be proven that the utility was negligent in its common law duty to supply wholesome water in which case it could be liable for damages (Wood 1987).

Quebec's Environmental Quality Act of 1984 stipulates that utilities must take regular tests of the drinking water quality, and that the tests will be at the utilities expense. Every other province has adopted some form legislation aimed at regulating the quality and character of its environment as well, however, except for Quebec, a good portion of the regulatory power at each province's disposal is rarely exercised. Most provinces rely only on non-enforceable water quality guidelines (Grover and Zussman 1985).

That is not to say there is no monitoring or control of water quality. In most provinces, water quality tests are regularly conducted by the department responsible for public health or the environment. In provinces such as Ontario, public water supplies may be shut down by local health officials acting under public health legislation if communicable disease organisms are detected in the water.

Standards for new water works construction can vary among the provinces both in substance and in purpose, with differences among provinces due to such things as climate, material availability, water quality, and ability to pay. In B.C., the Ministry of Municipal Affairs has developed a set of general development standards which set guidelines for both site planning and the engineering of roads and utilities (B.C. Municipal Affairs 1980). However these standards have not been adopted into regulations and act only as guidelines for municipalities. In Alberta however, under the Clean Water Act (1988) and the accompanying Clean Water Regulations (Municipal Plant), municipal water supply systems must now be designed to meet a variety of mandatory requirements (Alberta Environment 1988). The mandatory requirements related to water distribution design are as follows:

- pipe materials must adhere to Canadian Standards Association (CSA) standards for potable pipe or where no standards exist for the specific material, adherence to other standards (eg. AWWA, CGSB, NSF) may be considered by the Director of Standards and Approvals,

- all thermoplastic pipe must be manufactured from a resin conforming to CSA standards,

- water mains designed to carry fire flows must be a minimum of 150 mm diameter,
- minimum depth of cover must be 2.5 meters or more where required,
- specifications for shut-off valve and air release valve locations, minimum separation of water and sewer lines and manholes, and main disinfection procedures must be adhered to.

The Alberta regulations also provide non-mandatory guidelines for pipeline configuration and suggested operating pressures.

2.4. Factors Prompting Rehabilitation

Reduced funding levels, combined with steady deterioration of the water distribution systems, has resulted in the current backlog of necessary work and has caused many communities to become very concerned with the condition of their water systems. A recent survey of 300 Ontario municipalities show the areas of primary concern are with water quality, high break frequency, poor pressure, and system leakage (see Table 2.6).

Table 2.6: Areas of primary concern in Ontario's water distribution systems

Concern	Percentage of Communities with Concern as Priority
Water Quality	29.5
Break Frequency	21.9
Pressure	19.7
Leakage	14.5
Other	14.5

Source: Adapted from McIntyre and Elstad 1987

There are three primary sources of the concerns in Table 2.6 which, to varying degrees, drive a utility to consider the need for rehabilitation:

1) the desire to minimize costs,
2) the desire to maintain adequate levels of service, and
3) the desire to satisfy public demands and minimize public concerns.

The concerns with breaks and leakage are related primarily to the desire to keep down costs due to repairs, liability, and lost water. The concern over reduced pressure and flow is closely related to the desire to maintain service standards related to domestic use and fire flows. The desire to maintain water quality is aimed at instilling confidence in the public regarding health concerns.

Frequently the desire to maintain the cost and service level criteria are outweighed by public concern, which can rapidly be transformed into action via the political process. This is probably the most variable factor affecting a utility and there are a number of indicators that it may becoming more important. Today's concern with the health, the environment, and economic development all factor into the decision process, even when there are only perceived effects which are not validated by conclusive evidence, as is the case with the debatable concern over asbestos-cement pipe.

The following section will briefly outline some of these concerns to allow a greater appreciation for today's situation which in many ways is much different than that which existed when many of the systems were installed.

2.4.1. Increasing Maintenance and Operation Costs

Deterioration of a piped system is commonly measured in terms of the maintenance required to repair pipe failures, which are usually in the form of leaks or breaks. While all piped systems, regardless of age, experience such failures, unusually high failure rates and increasingly expensive maintenance costs indicate the need for rehabilitation. McIntyre and Elstad (1987) and MacLaren (1983) both estimate the average cost of a break in Ontario at $3,000.

Before continuing on, it is important to introduce a point of confusion common to the literature and statistics dealing with pipe failure. While it may seem intuitively obvious what a break and a leak are, there are a number of interpretations in the literature. For instance, Moruzzi (1987) defines a break, which he refers to as a "failure", as a macroscopic discontinuity which interrupts the regular flow of a pipe, while leakage refers to damage which causes a loss of water without interruption of the flow. Leaks and breaks are then mutually independent, meaning a particular system could have a large number of breaks, yet little leakage and visa-versa. In contrast, the AWWA (1986a) defines a break as a special type of leak, with "leak" being a more universal term for pipe failure. This incongruence pervades much of the literature and the statistics regarding leaks and breaks; in many cases the definition being applied is not forthcoming. The FCM (1984) estimated the historical increase in breakage rates in Canada, and although not explicitly stated, probably based the definition of a "break" on a repair being carried out due to the noticeable presence of water on the surface, be it from a leak or a break.

From 1968 to 1983, the FCM (1984) estimates the average breakage rate in Canadian systems nearly doubled, increasing from 16.6 breaks per 100 kilometres to 30.4. This is comparable to the 25 breaks per 100 kilometres per year now experienced in the U.S. and Britain, where the excessive deterioration of water systems have already been recognized (FCM 1984).

During this same period, emergency and scheduled repairs in Canada were estimated to have increased by 27 percent, from just under $5 per capita to approximately $6.25, while per capita pipe replacement expenditures only increased by 15 percent, from $5.70 to $6.56. Also during this period, average operation and maintenance expenditures increased by approximately 42 percent, from just over $7 per capita to $10. All figures were based on 1983 dollars and utilized the ENR index for comparison purposes.

While it is tempting make generalizations from these types of figure, it must be realized there is a great deal of variance among communities. McIntyre and Elstad (1987) found the current average annual break rate in Ontario to be approximately 25 breaks per 100 kilometres, which is close to the national average, but of the 436 communities supplying system length data, 111 were experiencing no significant breakage problems. Of the remaining 325 communities, only 47 percent were experiencing breakage rates above the provincial average. Thus, while breakage problems are significant, they are often concentrated in a relatively small number of communities.

It is interesting to note that of the 35 Ontario communities which experienced breakage rates in excess of 100 breaks per 100 kilometres per year, 34 were in small communities under 7,500 in population. McIntyre and Elstad (1987) feel that this indicates a large number of small systems are located in adverse conditions which leads to a disproportionately high share of the local resources being spent on the almost constant repair of the water distribution system.

The increase in break repairs is not the only source of increased expenditures. Excessive leakage from deteriorating systems means pumping energy, treatment chemicals, and raw water are wasted. Tate and Lacelle (1987) estimate that 12.4 million cubic meters (MCM) flowed through municipal systems on an average day in 1986, with 26 percent of the volume not accounted for. Of this, they estimate 20 percent is attributable to leakage or other waste and represents 240 million cubic meters per year, which is enough to fill up a 4 meter square by 1.5 meter deep swimming pool behind every household in Canada.

Dealing with the leakage problem is difficult due to the inability to easily detect leaks. Over time, even the smallest leaks can lose enormous amounts of water without any noticeable signs on the surface. The fact the pipes are buried hides much of the loss. To illustrate the scale of leakage that can occur and can be detected when the pipes are easily accessible, take the case of Paris, France presented by Versanne (1987). The Paris water system is unique in that it consists of two parallel systems, a drinking water system with 1,800 kilometres of pipe, and a non-drinking water system with 1,600 kilometres of pipe. The system is also unique in that 96 percent of the pipes are accessible, being located either in special water main galleries or sewer tunnels, and leak inspection can be carried out visually. The breakage rate on the drinking water systems reported by Versanne (1987) is equivalent to the Canadian average of 30 breaks per 100 kilometres per year, yet the system develops an average of 15,000 leaks per year which translates into 833 "leaks" per 100 kilometres per year. While it must be realized that only 10 percent of the Paris system was installed since 1955, compared to 70 percent in Canada, this case still emphasizes the scale of the problem that can potentially develop.

While there is little historical data to suggest the leakage problem has been worsening in Canada, there is evidence which suggests today's leakage from municipal water systems may is too high. Part of the information problem is rooted in the present attitude toward leakage. Hennigar (1984) notes that while the AWWA suggests system leakage in the order of 10 to 15 percent is reasonable, in Europe, after extensive leakage surveys, rates of 5 percent are now considered high. Outside of the municipal water industry, pipeline leakage rates are also much lower. The Energy Resources Conservation Board, which is responsible for monitoring over 204,000 kilometres of gas, oil, and water lines used by the energy industry in Alberta, reports average water line leakage rates of only 1 per 100 kilometres per year, and gas lines leakage rates of only 0.2 per 100 kilometres per year (ERCB 1983). Leakage as defined by the ERCB includes both ruptures (ie. breaks) and leaks.

The third significant result of system deterioration is capacity loss. This is typically due to corrosion products on the interior of the pipe wall or increases in demand needed to meet fire flows or system expansion. In any case, the typical operational response is to increase the flow and pressure through increases in pumping capacity. Such action can increase pumping costs as both increased energy is consumed and increased capital may be required. In addition, further stresses due to increased pressures are placed on existing distribution systems.

2.4.2. Fire Protection and Liability

Wood (1987) reviews some of the legal aspects related to the provision of water supply systems as they apply to Ontario law. If a municipality in Ontario exercises its right to establish a water system, it has a statutory duty to supply an uninterrupted supply of water to all of its customers, it has a common law duty to supply a "wholesome and pure supply of water to the consumer", and it may at times be required to improve its water supply system in accordance with certain water resource statutes. Failing to comply with any of these duties can result in the risk of liability (Wood 1987). Although the points outlined specifically apply to Ontario, they do illustrate principles common to other parts of Canada.

The recent trend in North America toward increased litigation has not left public utilities untouched. Lawsuits resulting from water distribution system operation have historically resulted from flood damage due to main breaks, though more recently a claim has succeeded against a municipality for failing to provide adequate fire protection.

The potential for liability due to flooding damage is a key determinant in the maintenance strategy of some utilities. As Bratton et al (1986) notes:

"In recent years, the courts in British Columbia have held the water utilities responsible under nuisance law for all private property damage. This imposition of absolute liability now requires that the decision to replace or rehabilitate a water main must consider the probability of a major damage claim with a water main failure. To wait for the development of a failure history upon which to base a replacement decision could result in a utility facing a multi-million dollar lawsuit."

The increasing values of real estate, especially in downtown cores, makes the consequences of such liability even more pronounced. Bratton et al (1986) estimates that a water main break in Vancouver's downtown business district will result in $48,500 worth of damage when it is on a high pressure main (100 to 150 psi), and $21,000 when on a low pressure main (40 to 70 psi). Conversely, a break in a residential area will result in an average of $6,000 worth of damage regardless of the pressure. All of these values are calculated using a weighted average based on the probability of occurrence of specific damages and historical data using a 300 mm diameter pipe.

The provision of fire protection is an aspect of water distribution that is solely the decision of the local authority. However, once a municipality makes a decision to provide fire protection, it is now obligated to provide reasonable service or face potential liability. A 1988 decision of Supreme Court of Canada (Laurentide Motels v. City of

Beauport) deemed the City of Beauport, Quebec (pop. 60,000) liable for $2.5 million in additional fire damages to a hotel caused by an inoperable fire hydrant. In the court's conclusions, L'Heureux-Dube J. (SCC 1989) commented,

> "In the case at bar the city of Beauport exercised its discretionary power to create a firefighting service (a policy decision) and, in light of the by-laws adopted in this regard and the other facts presented in evidence, the municipality undertook, at the very least by implication, to maintain this service and ensure that it was in good working order (an operational decision)."
>
> "...the fact that a municipal corporation makes a policy decision or refuses to do so does not entail its civil liability. If, however, the municipal corporation exercises its powers, discretionary or otherwise, so as to make its decision operational, subject to public law, it can be held liable for any damage caused to another through its fault, or through that of its employees in the course of their duties, unless the enabling legislation expressly excludes such liability or authorizes the municipal corporation to exonerate itself from liability."

While the liability regarding the proper provision of fire protection has been less pronounced, there exists the potential for high liability costs barring any changes in legislation. Excluding farm and vehicle fires, in 1987 there was approximately $821 million in property losses due to 41,405 structural fires in areas potentially served by municipal water systems (IBC 1989). This translates into an average loss of almost $20,000 per fire.

The recent movement by the courts regarding such liability have become a source of concern for many Canadian communities. In many communities, the distribution systems do not meet the fire flow requirements as set out by the Fire Underwriters Survey, partially due to deterioration and partially due to the presence of small diameter mains (FUS 1981).

A survey of 12 large (> 100,000), 15 medium (20,000-50,000), and 35 small (< 10,000) Canadian communities reported on by Wareham and McBean (1985) concludes approximately half of the communities have difficulties meeting the FUS requirements. The problems are most pronounced in the small and medium sized communities, of which an estimated 33 percent are expected to have future difficulties. In especially the small communities, relaxation of the FUS guidelines is common. Dead-end hydrants and inadequate fire flows due to small diameter mains are typical. Overall, the three most common reasons for not meeting the requirements are:

1) insufficient additional storage,
2) the continued replacement of old buildings with larger, new buildings without replacement of the old mains,
3) small diameter mains in the distribution network.

Wareham and McBean (1985) conclude that the problem is not easily solved. There is often little incentive on the part of a community to upgrade partly due to the slowness of insurance companies to compensate or reduce premiums in accordance with a community's endeavour to meet the FUS requirements.

Still, the inability of a system to provide adequate fire flows is only one consideration with respect to fire protection. System reliability in the event of an emergency is also usually not well known, though there have been recent developments in reliability analysis over the past few years to improve this situation (ASCE 1989). The presence of deteriorated mains which are susceptible to collapse from negative pressures during high flow fire events remains a factor in the provision of service.

The FCM (1991a) also suggests that for communities located in seismic areas, the ability to fight widespread fires and provide necessary drinking water after an earthquake is compromised by the presence of old outdated cast iron water mains which are subject to damage. Cast iron mains are very brittle and have only one-tenth the ability to withstand earthquake shocks (FCM 1991a), yet are prevalent in many Canadian systems.

2.4.3. Health Concerns

Water is the ultimate solvent and as such it can effectively dissolve substances both beneficial and deleterious to human health. As Morrison (1984) notes, when assessing drinking water, one must keep in mind "pure" water really means "wholesome" water, and that all drinking water contains chemicals and ions that actually make it taste good, rather than flat and insipid like distilled water. When considering the implications of a toxic substance in drinking water as it relates to human health, what is important is not only the presence of the substance, but its concentration. In setting water quality standards, the maximum allowable concentrations of such substances are based on lifetime exposures with average daily consumption using experimental data and applied factors of safety for risk control.

2.4.3.1. Water Quality Standards

The responsibility of the public health community is typically threefold: firstly, for assessing the risk associated with potentially harmful substances; secondly, for determining the maximum allowable concentrations which can be taken in by a human while still maintaining good health; and finally, recommending standards which incorporate the results. In theory, the process is straightforward and scientific, but a number of factors make the process less than ideal.

In past 25 years, the development of mass spectrometers and gas chromatography have rapidly advanced the science of analytical chemistry. Today, not only can new substances in water be detected which were undetectable in the 1950s and 1960s, but the substances can be detected at incredibly low concentrations of parts per billion and parts per quadrillion. However, many authors have stressed that analytical chemistry is still running orders of magnitude ahead of the ability of toxicologists and epidemiologists to determine the consequences of exposure to such minute quantities (Cotruvo 1984, Morrison 1984, Mannion 1988). Toxicology has strict limitations in that it simplifies the real world, looking at one chemical in isolation and its affects upon one animal, usually a laboratory mouse. Standard setting is based largely upon a health agency taking this often marginal information and extrapolating it to determine the impact of life-long exposure on humans (Hall 1984). In the cases where there is little conclusive data, agencies typically try to err on the safe side and draft conservative standards. As McColl (1985) points out, factors of safety can range from 2 to 4 for most inorganic toxins to 500 to 1000 for non-carcinogenic organic toxins (such as pesticides).

The Canadian drinking water standards are exceptional in that they are more extensive than those of many other countries, including the U.S., and the sampling of water supplies is more frequent (McColl 1985). One difference between American and Canadian standards which has a direct impact on the rehabilitation of piping systems is in the level set for the presence of asbestos fibres, which can originate from the leaching of asbestos cement pipes by soft or pH depressed waters. Studies on the occupational hazards associated with breathing in asbestos fibres are quite conclusive, yet there is limited information on the cancer-causing effects of ingestion (Hickman 1984). Canadian water quality guidelines do not include a provision for asbestos; as Health and Welfare Canada (1989) point out, the "assessment of data indicates no need to set a numerical limit." In the United States the EPA has proposed a recommended maximum contaminants level (RMCL) of 7.1 million fibres per litre for asbestos fibres longer than

10 um, but this has proven to be quite controversial, as the limits seem to have been based only on the proven carcinogenicity of inhaled fibres (AWWA 1986b).

A number of other substances directly related to pipe systems are or may soon be included in the Canadian guidelines. Vinyl chloride, a constituent of P.V.C. pipe, is currently under consideration to be added to the guidelines. The Canadian guidelines also make note that where lead is still a component of many plumbing systems, faucets should be thoroughly flushed prior to use.

Still, while there is concern over piping materials and their impact on human health, for the most part concern is limited and the public perception is that the danger is negligible.

2.4.3.2. Sources and Impact of Contaminants

Although a number of contaminants are identified in the water quality guidelines, the guidelines are not enforceable and in some communities the contaminant levels may be and often are exceeded. It is difficult to know whether this is causing serious health effects for a number of reasons: first, in Canada there is a perception that water borne diseases and the ill effects of contamination are at extremely low levels, but Grover and Zussman (1985) note that reported deficiencies in the national reporting system responsible for detecting such effects have led many health officials to believe a large number of local incidents go unreported. Secondly, drinking water is not the sole contributor of contaminants to the human body as food, air, and even absorption through the skin also contribute. Thus drinking water cannot be looked at in isolation as it is contributing only a portion of the total amount of total daily intake of certain substances; for instance drinking water contributes an estimated 45 percent of a Canadian's total daily intake of trihalomethane (THM), but only 3 percent of the mercury, 1.2 percent of the lead, and 0.06 percent of the cadmium (Hickman 1985). Finally, doses of contaminants and their effects on the population are highly variable. For instance, approximately two percent of Canadians drink more than two times the national average intake of 1.34 litres per day, which in effect means the dose they are receiving has increased by two, or similarly the factor of safety used in setting the drinking water guidelines has been reduced by one half. On a dose per kilogram of body weight basis, small children are more at risk than adults, who also have the added benefit of drinking a large proportion of their water boiled (in tea or coffee) which further reduces the content of volatile organics (Hickman 1984).

The impact on health of deteriorating distribution systems is usually overshadowed by the concern over quality of the raw water supply sources. Recent news articles have focused on the contamination of the Great Lakes which supply major cities such as Toronto with drinking water and which are known to contain levels of mercury, lead, pesticides, PCB's and other toxic substances in concentrations that exceed both U.S. and Canadian water quality objectives (Macleans 1990). But contaminants do not exclusively originate in the raw water source.

Hickman (1984) outlines the three main sources of chemicals commonly occurring in drinking water:

1) substances affecting the source quality (raw water),
2) substances resulting from treatment,
3) substances arising from the distribution and service systems.

The substances affecting the source can include: naturally occurring substances leached from soils, sediments, or geological formations (e.g. calcium, heavy metals), pollutants derived from point sources such as domestic sewage treatment, industrial effluent, or landfills (e.g. synthetic organics, metals, cyanide), and pollutants derived from non-point sources such as agricultural run-off, urban runoff, and atmospheric fall-out (e.g. fertilizers, pesticides, salt, chlorinated organics, PAH's).

Substances resulting from treatment can include those formed during chlorine disinfection (e.g. trihalomethanes, chlorophenols) plus treatment chemicals (e.g. chloramines, fluorides) and their impurities (e.g. acrylamide monomer, carbon tetrachloride).

The third source of drinking water contaminants is the most relevant to this discussion. Substances which arise from the distribution and service systems include contaminants arising from contact with constructional materials and protective coatings (e.g. lead, vinyl chloride monomer, asbestos fibres from piping, cadmium from fittings, PAH's from coal tar linings) as well as from point-of-use devices, such as home carbon filters (e.g. sodium, silver).

In Canada, though federal water quality guidelines do not include a provision for asbestos, there still exists concern over the health effects of it. Considering there is as much as 13,000 kilometres of A.C. pipe in Canada, the implications of more stringent standards are broad and expensive.

Studies have been carried out in Canada using the U.S. EPA standard of 7.1 million fibres per litre (MFL) as a basis for discussion. Hickman (1984) notes that Winnipeg, which has both aggressive waters and substantial amounts of A.C. pipe, has taken samples from the distribution system containing 6.5 MFL, while samples at the treatment plant only contain 0.3 to 0.4 MFL, indicating a substantial amount of the fibres are from the distribution system. Hunsinger et al. (1989) points out that asbestos fibres are also found in natural waters, which can be removed by conventional water treatment, and of 268 surveyed Ontario communities, only one percent of the samples exhibited levels greater than 7.1 MFL for fibres of all lengths, and none had long (> 10 um) in concentrations exceeding 7.1 MFL. Only three supplies showed treated water as having more than 7.1 MFL of all sizes, with the chance of encountering fibres longer than 10 um at these locations calculated to be less than 0.01 percent.

Metal pipes can also introduce substances into treated water. Lead pipes and lead joints, though discontinued for use several decades ago, are especially prone to leaching in the presence of soft, aggressive waters and still do exist in some older urban cores (Morrison 1984). Copper and galvanized steel services have also been documented to contribute excessive lead through the deterioration of solder joints, especially in the presence of aggressive waters where protective calcium carbonate films can not form, and especially when the water stands for long periods of time in the pipes (McClelland 1981, Hickman 1984). Millette and Mavinic (1988) found copper and iron concentrations which exceeded the national guidelines by 100 to 300 percent in a number of locations in Vancouver, which has an aggressive, soft water with little buffering capacity.

Plastics can also contribute to the contamination of drinking water through leaching, though Hickman (1984) notes that plastic pipes certified by the National Sanitation Foundation (NSF) are not problematic. McClelland (1981) provides an excellent overview of the standards and testing procedures used by the NSF and stresses the fact that plastic pipes are highly regulated and tested, especially when compared to pipes of other material (e.g. metal). The NSF, through a voluntary testing program with the manufacturers, checks for compliance of P.V.C. pipes regarding content of certain metals (e.g. antimony, arsenic, barium, cadmium, chromium, lead, mercury, selenium, and tin) and residual vinyl chloride monomers (RVCM) which can be transferred to water in use. In Canada, the CSA (Canadian Standards Association) provides standards comparable to those provided by the NSF in the U.S.

Bacteria can sometimes thrive in water distribution systems. Pathogens such as those responsible for Legionnaires disease have been found in Canadian water systems (Grover and Zussman 1985). Pathogenic coliform can reproduce and migrate in distribution systems especially if the residual chlorine is low, turbidity is high, or scaling and tuberculation are high (AWWA 1988). Generally, such bacteria are present due to two mechanisms: breakthrough and growth (AWWA 1988). Breakthrough refers to those bacteria which pass through the disinfection process, while growth refers to the increase in bacteria due to their continued growth downstream of the treatment plant. Models aimed at predicting the chlorine residual in distribution systems are being developed to combat this problem (AWWA 1988).

Growing concern over the quality of tap water has proved a boon to the bottled water industry, which had sales of $150 million in 1989. Recent tests have shown that some bottled waters, which are not as stringently regulated as tap water, contain high levels of barium and bacteria which probably resulted from the contamination of the source, which is typically a groundwater "spring" (Macleans 1990). As of January 1990, only Quebec had in place regulations for bottled water quality (Macleans 1990).

An additional response by consumers has been to purchase point-of-use water treatment devices, but there are a number of concerns with these devices as well including the accumulation and concentration of metals and pathogenic bacteria in filters (especially ones which are infrequently changed or operating on raw water) and the false claims made by sales people as to the effectiveness of such filters (Grover and Zussman

1985, Hickman 1984, Macleans 1990). In 1984, an estimated 3 percent of Canadian homes had point-of-use filters, with half being activated carbon (Grover and Zussman 1985).

2.4.4. Impending Changes in the Rules

Various levels of government are looking to change some of the existing practices dealing with water supply in Canada. The federal government is looking to assure water quality across the country through the introduction of mandatory federal regulations. Local governments concerned with rising liability claims are looking to develop consistent benchmark standards to measure maintenance against. Such changes could have a potentially huge impacts within the next five to ten years and merit some discussion here.

Although the quality of drinking water has been traditionally a provincial responsibility, the federal government through the Department of Health and Welfare is preparing to introduce legislation for a Canada Drinking Water Safety Act. Currently Canada remains one of the few developed nations without a federal law requiring minimum drinking water quality standards (Environment Canada 1990b).

In the U.S. for example, the Safe Water Drinking Act of 1974 set out "to constitute a cooperative venture among federal, state and local levels of government, by requiring the establishment of consumer oriented drinking water regulations" (Grover and Zussman 1985). However, implementation of the Act was not without its political and administrative problems. While the Act provided for funds to the States to help cover the administrative costs of implementing the new legislation, there was no money set aside to help utilities with the needed improvements to comply. This problems was particularly acute among small communities which inherently have a very limited tax base; the economies of scale associated with water treatment meant the small communities had to pay considerably more per capita than the larger centres.

In Canada there is no national "code" regulating the design or maintenance of water works. The FCM (1989) has recognized the need for standards in Canada to help protect municipalities from the resulting risks based on the following rationale:

"... having standards in any given municipality has the advantage that, in case of claims involving litigation, the municipality itself will have a set the standards, whereas, in the absence of standards, a judge may do so, and he may choose a far higher and more expensive level of service as his standards. Our advice is that usually courts accept standards chosen by municipalities, providing they are reasonable and consistent. It appears that it is not necessary that they be common across the entire nation, as courts recognize that some municipalities have a lower ability to pay for service levels than others. Standards must be adopted politically and not merely be technical regulations."

The FCM's intent is to develop a set of national standards that are stringent enough to satisfy the courts, yet flexible enough to allow all municipalities to adopt the standards, regardless of their ability to pay. For this reason the standards will be somewhat general, with ranges of service levels based on established practice, rather than on the imposition of strict standards.

The FCM is currently developing design and service level standards for sewer collection infrastructure and plans to start development on similar standards for water systems (Curtis 1991a, FCM 1991b). The FCM hopes the standards, which are based on a survey of nine member municipalities, will lead to the wider adoption by other member municipalities and the eventual endorsement of them by the Canadian Public Works Association (FCM 1991b).

2.4.5. Environmental Concerns

Concern for the environment and the impact of development on it is growing. Conservation was the key in the 1960s and 1970s. Today, "sustainable development", a term introduced by the United Nations in 1980, is entering many facets of our lives. Sustainable development can be summarized as (IUCN 1980):

"the modification of the biosphere and the application of human, financial, living and non-living resources to satisfy human needs and improve the quality of human life. For development to be sustainable it must take account of social and ecological factors, as well as economic ones; of the living and non-living resource base; and of the long term as well as the short term advantages and disadvantages of alternative actions"

A number of authors suggest that "water demand management" promotes and encourages the objectives of sustainable development (Postel 1985, Tate 1990). Brooks and Peters (1988) define water demand management as "any measure which reduces or reschedules average or peak withdrawals from surface or ground water sources while maintaining or mitigating the extent to which return flows are degraded".

Postel (1985) suggests that demand management in water systems can save not only through the reduced demand for the water resource, but also through a reduction in the resources necessary to construct such systems. In the past, planners have tended to project historical per capita water demands to future population forecasts, rather than trying to focus on reducing demand over the long term. Postel (1985) suggests that reduced demands through more rational pricing can reduce the system capacities required, and thus the total cost of the systems.

Tate (1990) outlines the three basic techniques available for water demand management: economic techniques, structural and operational techniques, and socio-political techniques. These techniques will be discussed in more detail in later sections, but all basically involve reducing excess demand through the elimination of subsidies, the reduction in system water losses, and through the promotion of conservation.

The potential application of such techniques to municipal water supplies is great; in Canada, municipal systems use over 12 million cubic metres of water, constituting 16 percent of the total Canadian water draw, with at least 26 percent of this flow unaccounted for through system leakage, waste, discharges directly to return streams, fire flows discharged directly to storm sewers and to evaporation from lawns and gardens (Tate and Lacelle 1987, Tate 1990).

But the current concern for sustainable development can also have indirect effects on water distribution system development. Sustainability concepts promote changes in land use toward denser, more compact urban forms. Sustainability has also been used in arguments for tighter industrial emission controls which can affect both the atmosphere and eventually the quality and pH of the water source through acid rain.

Control of acid rain has been a prominent global issue in the past few years. The internal corrosion problems of water distribution systems can worsen if acid rain depresses the pH of the supply. Communities situated on the Canadian shield and the coasts are especially prone since the buffering capacity is very low for lakes and catchment areas situated on granite and igneous formations. Vancouver for instance has an average pH well below the Canadian recommended range of 6.5 to 8.5 and has been experiencing problems with corrosion of its copper services and cast iron mains (Millette and Mavinic 1987). A number of other communities in greater Vancouver are also experiencing wall softening and high breakage rates among their asbestos cement pipes due to the aggressive nature of the water (Robinson 1991, MacLean 1991).

2.4.6. Economic Development Considerations

The provision of efficient and cost-effective infrastructure is necessary to attract investment in any community both from public health and economic perspectives. In today's global marketplace, there is increasing competition among countries, regions, and municipalities to attract new industry which may result in new jobs and new prosperity. In the U.S., Williams (1984) points out the importance of municipal water systems to industry,

> "... according to a U.S. Commerce Department survey, the most critical community attribute that industry looks for in deciding where to relocate or expand is the availability of fire protection. That means the most important asset a community can develop is a reliable water system capable of delivering water at a sufficient pressure and flow. This is much more valuable and important to industry than tax incentives are. Yet Sates and localities continually compete with one another to ruin their tax bases."

Williams (1984) notes that in the same U.S. Commerce Department study, taxes were only one of many variables which influenced industry location, and in many cases made little difference in the final relocation or expansion decision. Costs of fire insurance and plant construction can be directly related to the community's ability to provide fire protection and the ability of the community to provide quality, reliable public services.

But the provision of quality services to attract development is not the only contributor which can enhance a community's prosperity. Development and improvement of infrastructure is labor intensive, and can generate much needed employment and the benefits of this. Studies have indicated that 35 to 40 person-years of employment and one quarter of a million dollars in expanded local business can result from each million dollar investment in water supply or sewer systems (Environment

Canada 1983).

Investment and financing in infrastructure are not only beneficial from an employment and economic perspective, but in many ways represent the heart of the current problems and the required solutions. According to Williams (1984), the infrastructure crisis is basically a financing problem. The current situation has not come about due to technological short-comings nor design or construction failures, but rather has developed through unfortunate political and fiscal decision-making. In attempting to solve the current dilemma in New York State, Williams makes five basic assumptions which can be extended to many other geo-political areas:

1) taxpayers must not have to pay higher taxes,

2) taxpayers can not be subject to further debt liability due to unforeseen circumstances such as municipal default,

3) there is no reason a person living in one city should have to pay for repairs in another city,

4) the solution must work within the given constitutional framework, and

5) revenues generated by a utility should stay with the utility and not go to support other general municipal services.

While any one of the assumptions may be challenged or debated, together they do form a basis for discussion required in developing a policy framework. Williams concludes that one solution lies in the creation of a State finance authority set up by legislation to provide bonding capacity to the local municipalities and to request loans and grants from federal programs on behalf of the local municipalities. Three financial options were put forth including loans, leaseback, and a revenue bond option.

Although each of the financial and political options just outlined will have a different degree of applicability within the Canadian context, one important point is brought forth: cooperation and coordination from all levels of government and financial institutions within the political context of each region is one key to overcoming the problem and enhancing the communities affected. The nature of the problem is diverse, and so should be the solution.

2.4.7. Public Concern

While all of the preceding discussions outline the concerns specific to the need for water system rehabilitation, it must be recognized that the overall importance of these issues to the public will be the main factor which determines whether or not the political will is there to get something done. Unfortunately, information gauging public opinions on these issues is very limited.

Grover and Zussman (1985) noted that while environmental health concerns were among the top ten issues covered by the Canadian media, only a fraction of the coverage concentrated on water pollution matters, and even less on drinking water issues. A Decima survey conducted for Health and Welfare Canada at the time placed concern for hazards from tap water as very low compared to three other categories which included food additives, air pollution, and pesticides. These findings led Grover and Zussman to conclude that while the long term interest in drinking water issues is quite low, when problems do arise Canadians demand immediate and remedial action. This conclusion is echoed by Anderson (1988) who postulates that the only way to draw attention to water supply issues is through crisis, yet once the crisis has passed, water supply again becomes a non-issue.

More recently there has been growing concern over drinking water quality in Canada, though much of the concern has been related to specific environmental issues such as the toxins in Lake Ontario. Still, according to a Gallup poll published in October 1989, 95 percent of those polled were concerned with the quality of drinking water in Canada (Macleans 1990).

How effectively this concern is being transformed into political action aimed at the improvement of water supply infrastructure has yet to be seen. Infrastructure rehabilitation was not a major issue in the 1988 federal election, as the FCM had hoped it could be, but did enter the 1993 election campaign on the basis of job creation rather than any deep concerns over health, the environment, or industrial need. Since the FCM's report in 1984, conferences and briefs have increased public awareness of the problem, but in the overall scope of day to day life, public concern over infrastructure is still not great. Indeed, the public sentiment over the proposed infrastructure program announced by the federal Liberals during the election campaign was one of scepticism, with the perception that the debt-burdened federal government would only be buying jobs with more borrowed money. Little attention was paid to the benefits that such a program might have on health or industry within the average Canadian community, an indication that the education gap is still quite wide.

CHAPTER 3: CANADIAN WATER DISTRIBUTION SYSTEMS INVENTORY

3.0. Overview

This chapter provides a look at the "pipe" beneath Canadian municipalities, representing a current "best estimate" inventory based on data which was accumulated from various sources and transferred by the author onto a spreadsheet program.

Unlike water treatment systems, there is no national inventory of the water distribution works within Canada even though the distribution system typically represents nearly 80 percent of a water system's value (Edwards and Cox 1981, MacLaren 1985).

Heinke and Bowering (1984) estimate that in 1981 there were 100,000 km of water main in Canada based on a served population of 20.3 million (FACE 1981) and an average "service density" of 200 persons per kilometre of watermain, a value extracted from a report to the Ontario Ministry of the Environment (MacLaren 1983).

The need for a comprehensive inventory of Canada's underground plant has been noted by a variety of sources (FCM 1984, MacLaren 1985, MacLaren 1991) but to date no agency keeps such records on a national scale. It is very difficult to discuss the efficient management of water systems in Canada without some basic information on the systems: how much pipe is in the ground? how old is it? what types and sizes of pipe are predominant? what are the soil conditions? what are the water conditions? what operating pressures are common? Unfortunately in Canada not even the first question can be answered with a large degree of accuracy. Although a variety of information exists within individual municipalities and some provinces, no agency has yet to compile a comprehensive national data base, although the 1984 FCM survey was a first step (FCM 1984).

In England, a comprehensive survey was carried out in 1977 from which courses of action could be taken (DoE and NWC 1977). Similar surveys in Canada have been carried out at a provincial level in Alberta (Grover 1990) and Ontario (McIntyre and Elstad 1987). The U.S. is currently basing much of its rehabilitation policy on system age (FCM 1984).

3.1. Data Sources and Methodology

Historical data from provincial municipal statistics reports, trade journals, annual reports of various cities, and past system surveys is used to estimate the amount of pipe beneath Canada's villages, towns, and cities (see Table 3.1). In addition, information on current consumption rates was also compiled.

Table 3.1: Data sources used in estimating the Canadian water pipes inventory

SOURCE	EXTENT	COMMUNITIES	DATA INCLUDED	YEARS
Denis 1912	National	all	Population; Pipe length, type, size range	1912
Municipal Utilities 1951	National	pop. > 1,000	Population; Pipe length, type, size range	1951
Municipal Utilities 1961	National	pop. > 1,000	Population; Pipe length, type, size range	1961
Provincial Municipal Statistics Reports	B.C.	all	Population; Pipe length	1951-88
	Alberta	all	Population; Pipe length	1943-88
	Ontario	all	Population; Pipe length	1934-67
	Nova Scotia	all	Population; Pipe length	1965-88
Annual Reports	Winnipeg	city	Pipe length	1931-86
	Montreal	city	Pipe length	1979-84
FCM 1984 (survey)	National	limited	Pipe length	1984
FACE 1975	National	all	Population served; Number of systems	1975
FACE 1978	National	all	Population served; Number of systems	1977
FACE 1987	National	all	Population served; Number of systems	1986
IWD 1990	National	pop. > 1,000	Consumption	1989

The procedure involved accumulating or estimating national water main data for four available years: 1912, 1951, 1961, and 1986. An estimate for 1991 is calculated based on average growth rates. Unfortunately, none of the data sources in Table 3.1 are ideal, neither individually nor when combined. Only the data source for 1912 contains a comprehensive listing of the Canadian systems (Denis 1912). While there remains major gaps in the data, what does exist is still very useful.

The data sources for the 1951 and 1961 estimates provide information for all municipalities greater than or equal to 1,000 in population (MU 1951, MU 1961), so the pipe in the smallest communities must be estimated by applying average pipe densities from the available data to the population served in these smallest communities.

The data base for the 1986 estimate is the least comprehensive. Comprehensive water main length information for nearly all communities in Alberta, British Columbia, and Nova Scotia is available from each province's respective "summary of municipal statistics" publication.

To estimate the pipe lengths in communities outside of these provinces, the data from the three provinces is aggregated and the average population served per kilometre of water main, or "service densities", are calculated for ten community population intervals. These service densities are then applied to the "populations served by water distribution" available in the FACE (1987) publication to give an estimate of the water main lengths. For some of the larger centres such as Winnipeg, Toronto, and Montreal information is extracted from each city's annual reports, while for some other communities, information is extracted from the FCM (1984) survey data base.

Although a rigorous statistical analysis is not performed, the sample provided by the 1986 data sources still represents 40 percent of the entire population served by water distribution systems in Canada, which constitutes a very good sample. While it is a major assumption to apply the pipe density for communities in Alberta, B.C. and Nova Scotia to other provinces like Quebec or Ontario, especially considering the differences in land use patterns and urban densities, the results obtained seem reasonable.

For a more detailed description of the data sources and the procedure used in formulating the national estimate, see Appendix A.

3.2. Results of the National Inventory Estimate

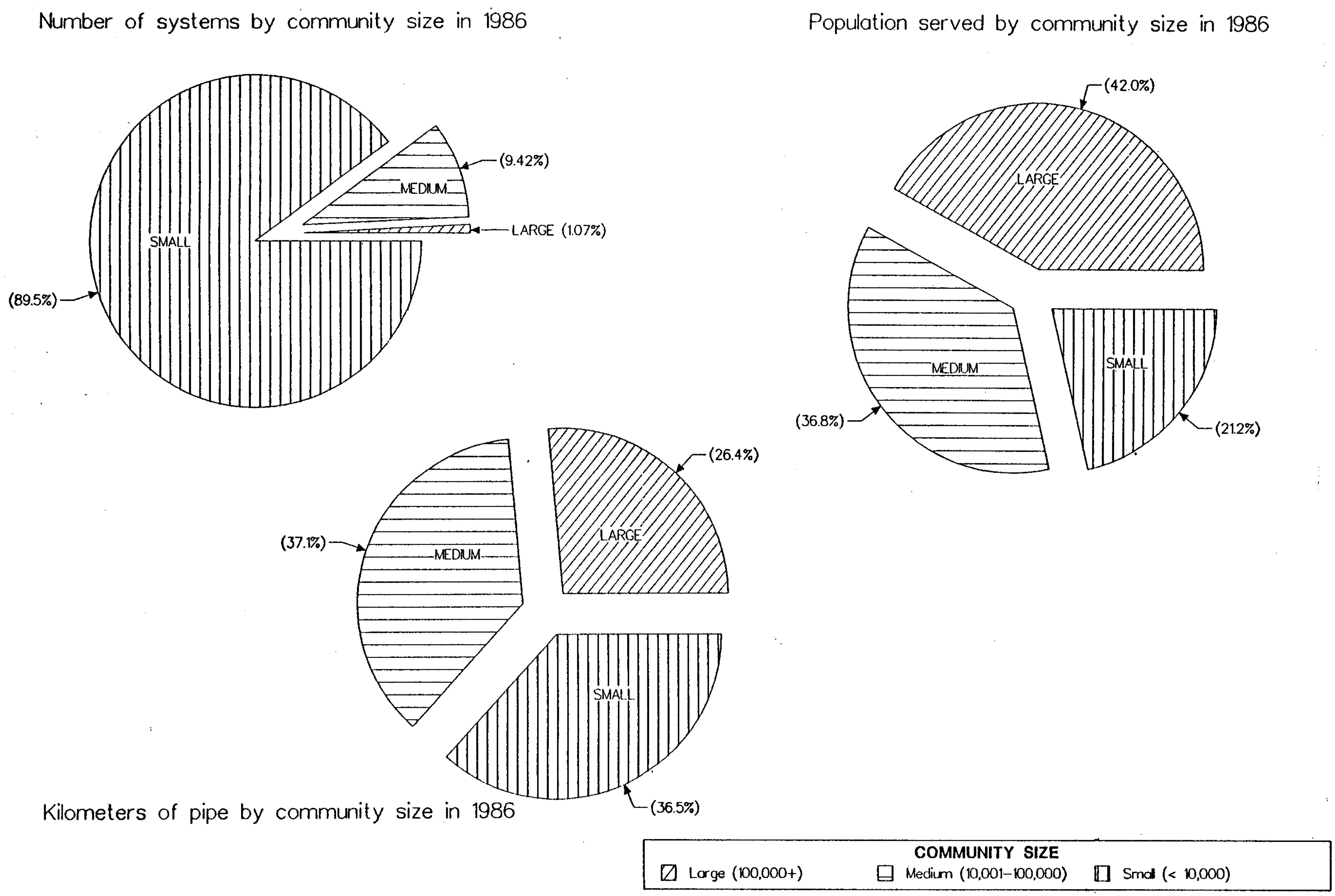
The inventory provides some basic information on the length, service density, age, material types, and diameters of the water distribution "pipes" in Canada as well as some general information on system demands.

3.2.1. Pipe Length and Service Density

From the inventory information, in the order of 23 million Canadians in 2,887 communities are served by approximately 130,500 km of water main, with this number growing from 1 to 2 percent annually, or about 2,000 km per year. Thus 85 percent of all Canadians receive their water from some type of shared water distribution system. Much of the remaining population resides in rural areas of the country and, for the most part, is serviced by private wells (FACE 1987).

Of all the systems in Canada, only 31 are located in large municipalities (100,000+), 272 are in medium sized communities (10,001-100,000), and 2,584 are in small centres (< 10,000). As can be seen in Figure 3.1, while there are relatively few large systems, they serve the largest percentage of the total population served (42 percent) yet contain the least total pipe length (26.4 percent) of the three population

Figure 3.1: Canada's water distribution systems



groups. Medium sized centres, on the other hand, do not exhibit such a discrepancy; the 272 medium sized communities represent 36.8 percent of the population and contain 37.1 percent of the pipe. Small communities represent the antithesis of the larger centres, serving only 21.2 percent of the population from 36.5 percent of the nation's total pipe.

The total pipe length calculated seems reasonable when compared to estimates from other sources. An average of 177 persons are served by each kilometre of water main in Canada, a figure similar to the density reported for the United Kingdom of 175 persons per kilometre (DoE and NWC 1977, Edwards and Cox 1981). MacLaren (1983) estimates that the Ontario density is approximately 200 persons per kilometre, while this study estimates it at 202 persons per kilometre.

The Ontario density is greater than the national average partly due to Ontario's higher proportion of large, dense centres. Toronto for instance has a service density of over 500 persons per kilometre of water main, or nearly three times the national average.

Table 3.2: Population served per kilometre of pipe in Canada

Population Interval	Persons per Kilometre of Pipe
500,001 - 1,000,000	313
100,001 - 500,000	261
30,001 - 100,000	180
10,001 - 30,000	159
5,001 - 10,000	114
2,501 - 5,000	112
1,001 - 2,500	106
less than 1,000	68
National Average	177

Source: Derived from data base in Table 3.1

There is a very strong relationship between the pipe density and size of community in Canada. From Table 3.2, one can see that the largest municipalities in Canada serve nearly five times as many people from the same length of main as do the smallest communities. Generally, the larger the community, the higher the service density. This general characteristic has existed historically and remains quite evident today as can be seen in Figure 3.2. It is also important to note that there has been a noticeable decrease in the service density across all population intervals over the past eighty years, indicating a general trend toward less intensive urban land use and higher levels of service.

As can be seen in Figure 3.3, there exists significant differences in service densities even among the largest cities in Canada. Older cities such as Toronto and Montreal have historically held higher service densities than younger cities such as Calgary and Edmonton, although the densities in the older cities appears to be decreasing with the development of less dense suburbs. The apparent increase in service density in Halifax is probably due more to an inaccuracy in the provincial data, rather than major increases in the city's density.

3.2.2. Age of Distribution Systems

As can be seen in Figures 3.4 and 3.5, the provision of water distribution service in Canada is only 150 years old, with the most rapid expansion coinciding with the "baby boom" following World War II. From Figure 3.5, the average age of Canadian water distribution systems in 1991 is calculated to be 31.9 years, which corresponds well with the average age of 25-28 years estimated in 1984 by the FCM, especially considering that seven years have passed since the FCM survey (see Table 3.3).

Figure 3.2: Canada's water works
Persons per kilometer of watermain by year

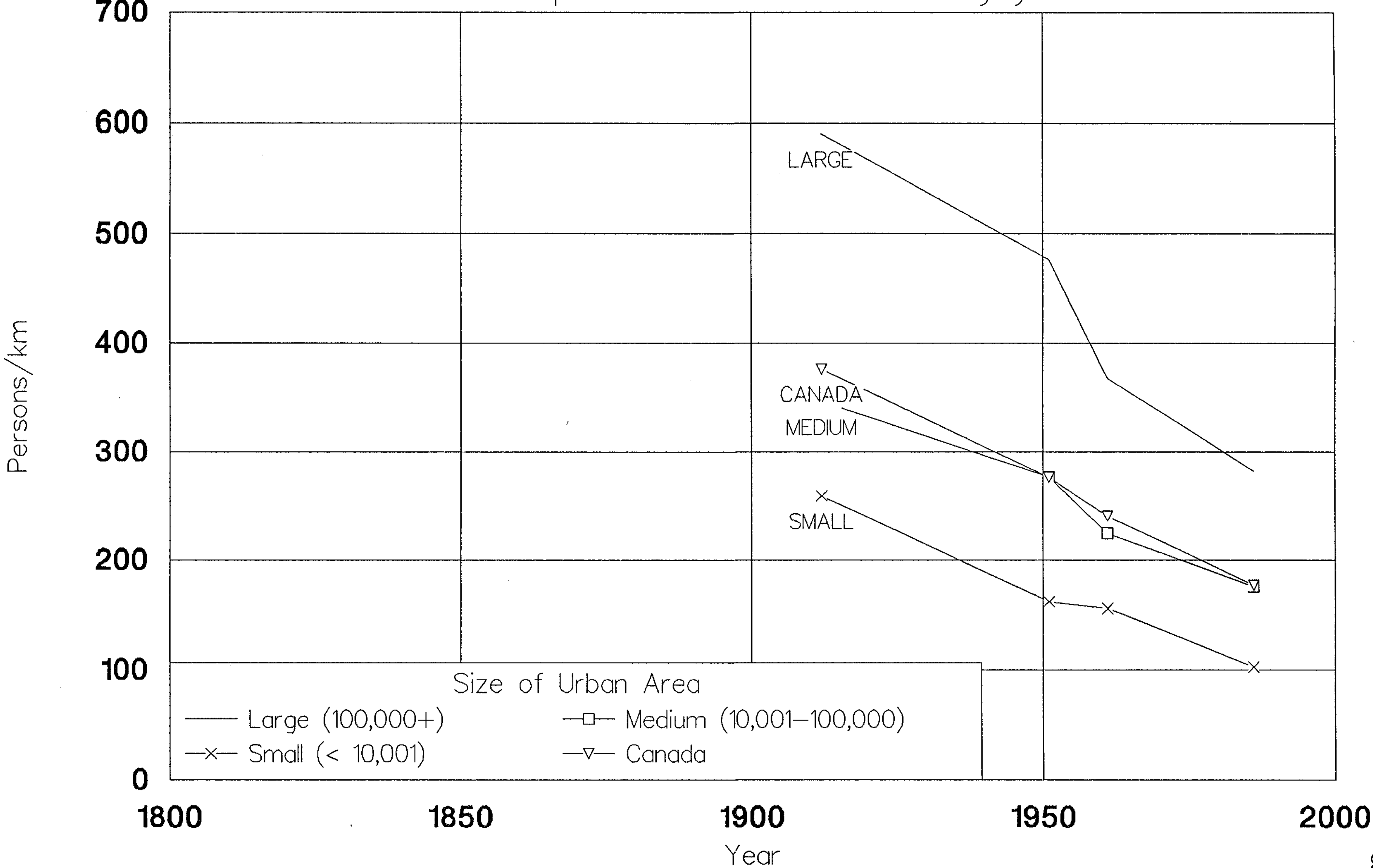


Figure 3.3: Canada's water works

Persons per kilometer of pipe in selected cities

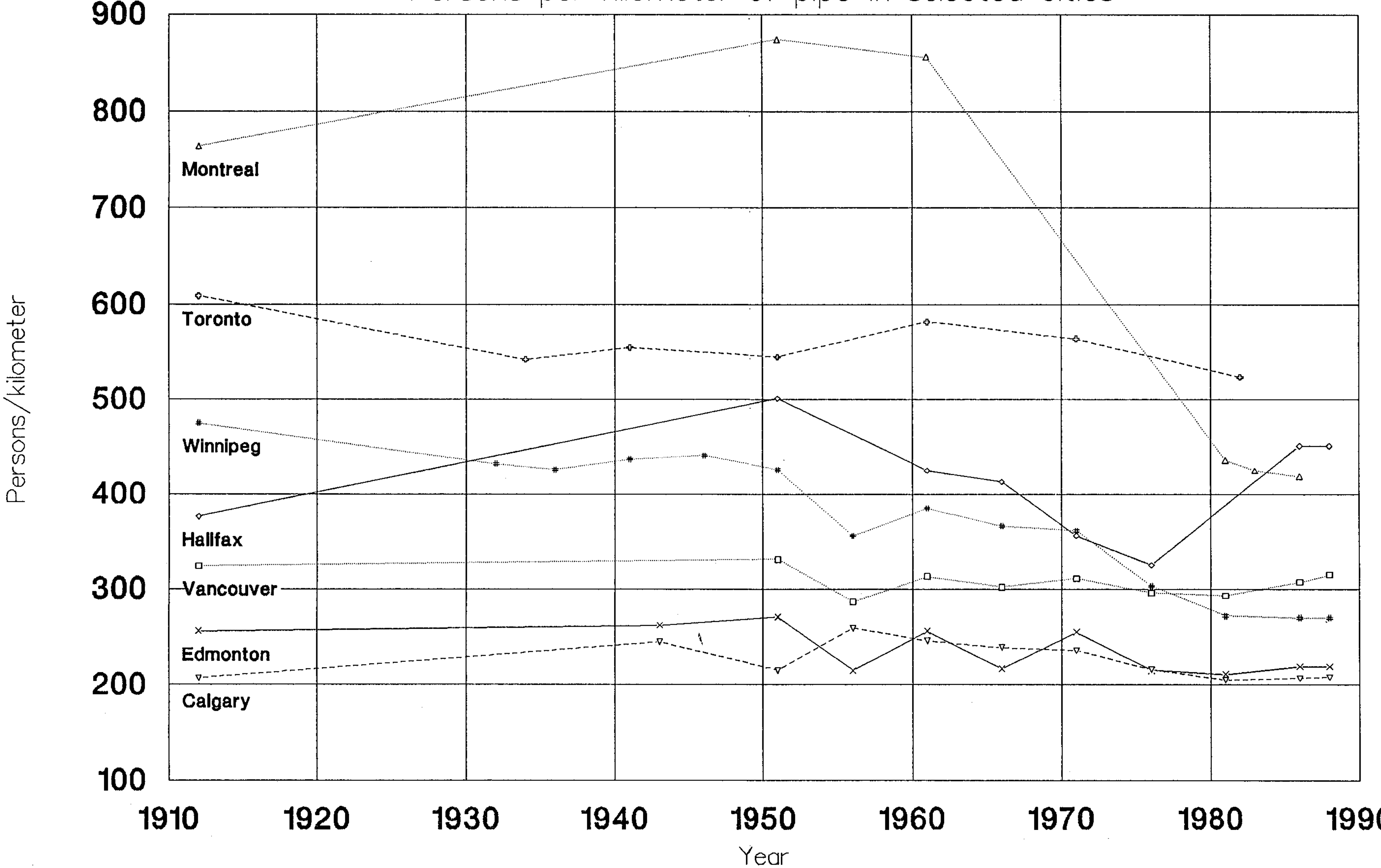


Figure 3.4: Canada's water works

Population served in surveyed communities by year

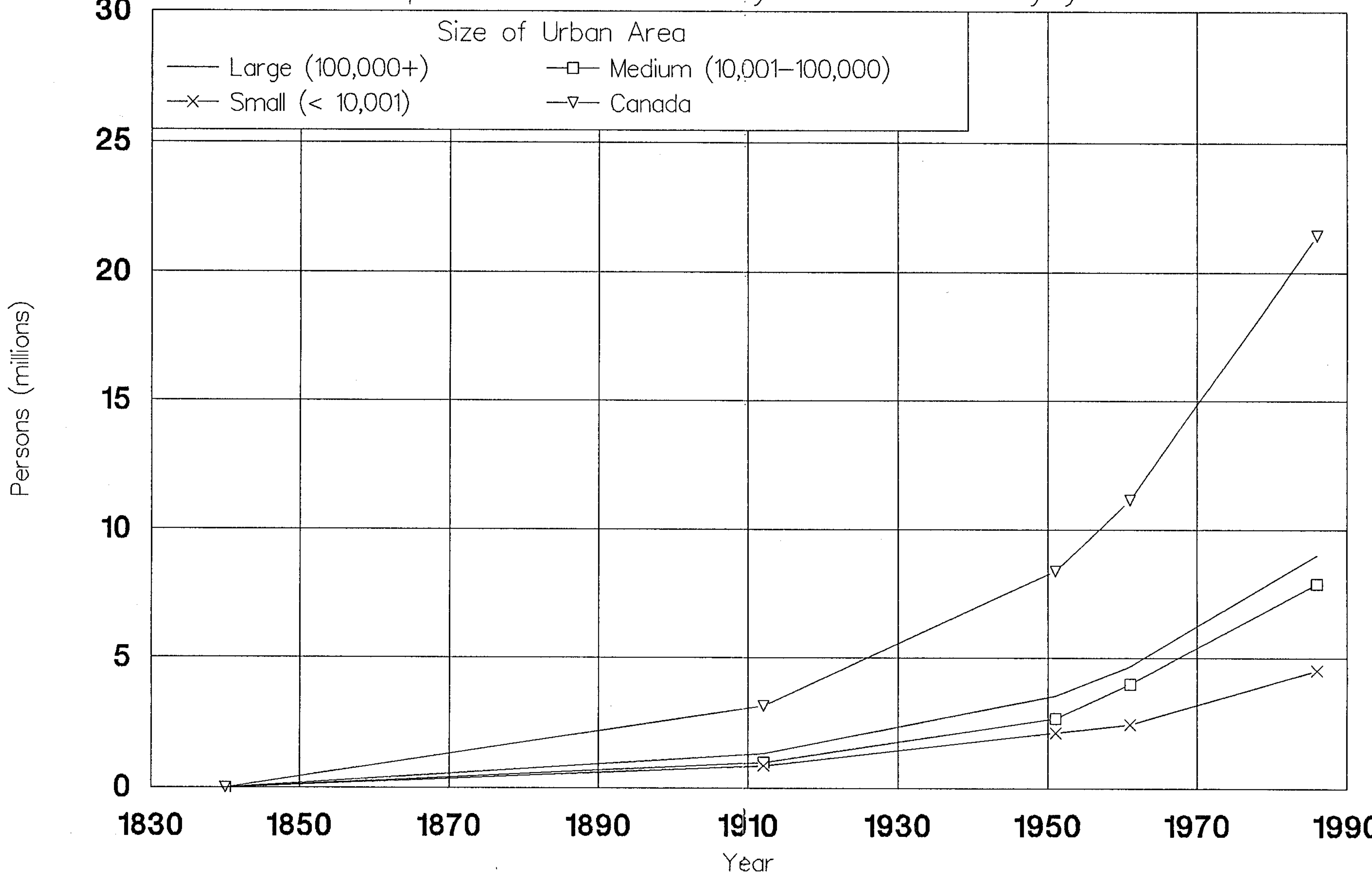
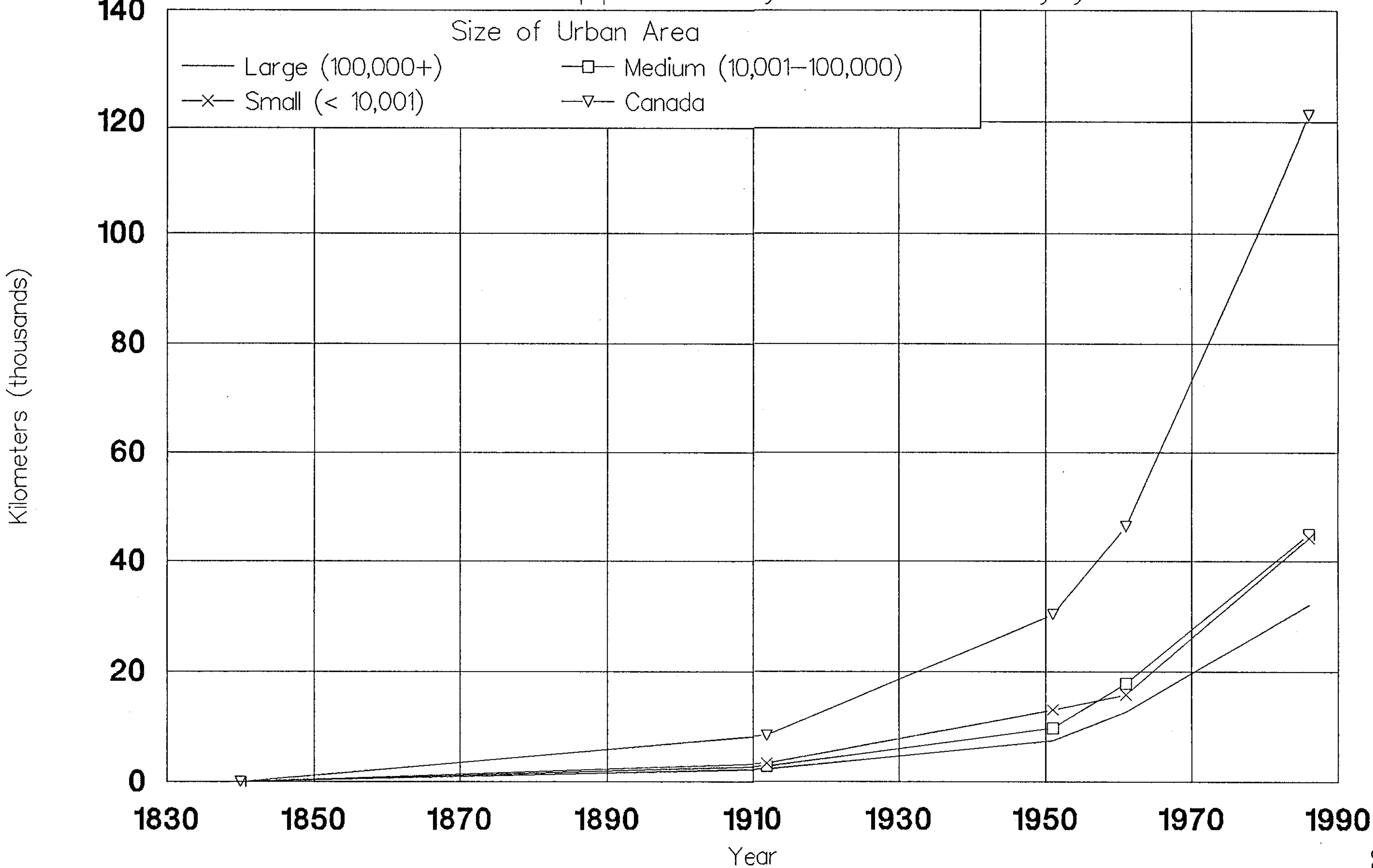


Figure 3.5: Canada's water works

Kilometers of pipe in surveyed communities by year



The specific age of Canadian systems varies from region to region and from city to city in Canada. Even within a community the age varies from area to area, with the oldest portions of the system usually located near the core. But because pipes wear out somewhat inconsistently, some sections of a system may contain the original pipe laid down when the systems was first initiated, while other sections may have been replaced once or a multitude of times.

Table 3.3: Estimated average age of distribution systems by region in 1991

REGION	AGE (Years)
B.C.	33
Prairie	28
Ontario	34
Quebec	30
Atlantic	32
CANADA	32

Source: Derived from data base in Table 3.1

The rate and nature of this replacement varies significantly and makes it difficult to obtain an exact picture of the general age of the Canadian system using this data.

In Toronto, Doherty et al (1987) notes that only 50 kilometres of Toronto's 1,227 total kilometres were replaced between 1968 and 1987, which translates into only 0.2 percent per year. At this rate, it would take 470 years to replace all the mains in the city. In Vancouver, Bratton et al (1986) notes that 370 kilometres of steel mains installed in the 1920's were replaced in the 1960's due to high leakage, representing over 26 percent of the city's current 1,400 kilometres of water main.

Because of the difficulty in determining national replacement rates, the age of the pipes determined in this analysis are based on an assumed zero replacement rate. While this may seem a major assumption, the relatively young average age of the systems in Canada probably means a great deal of the original pipes have not yet been replaced. Considering the close match between the FCM and this study's calculation of average age, this may be a reasonable assumption. Even if this assumption were to prove less than acceptable, Table 3.3 still can be thought to represent a "worst case" where none of the pipe in the ground has been replaced, or an average "time since first installation".

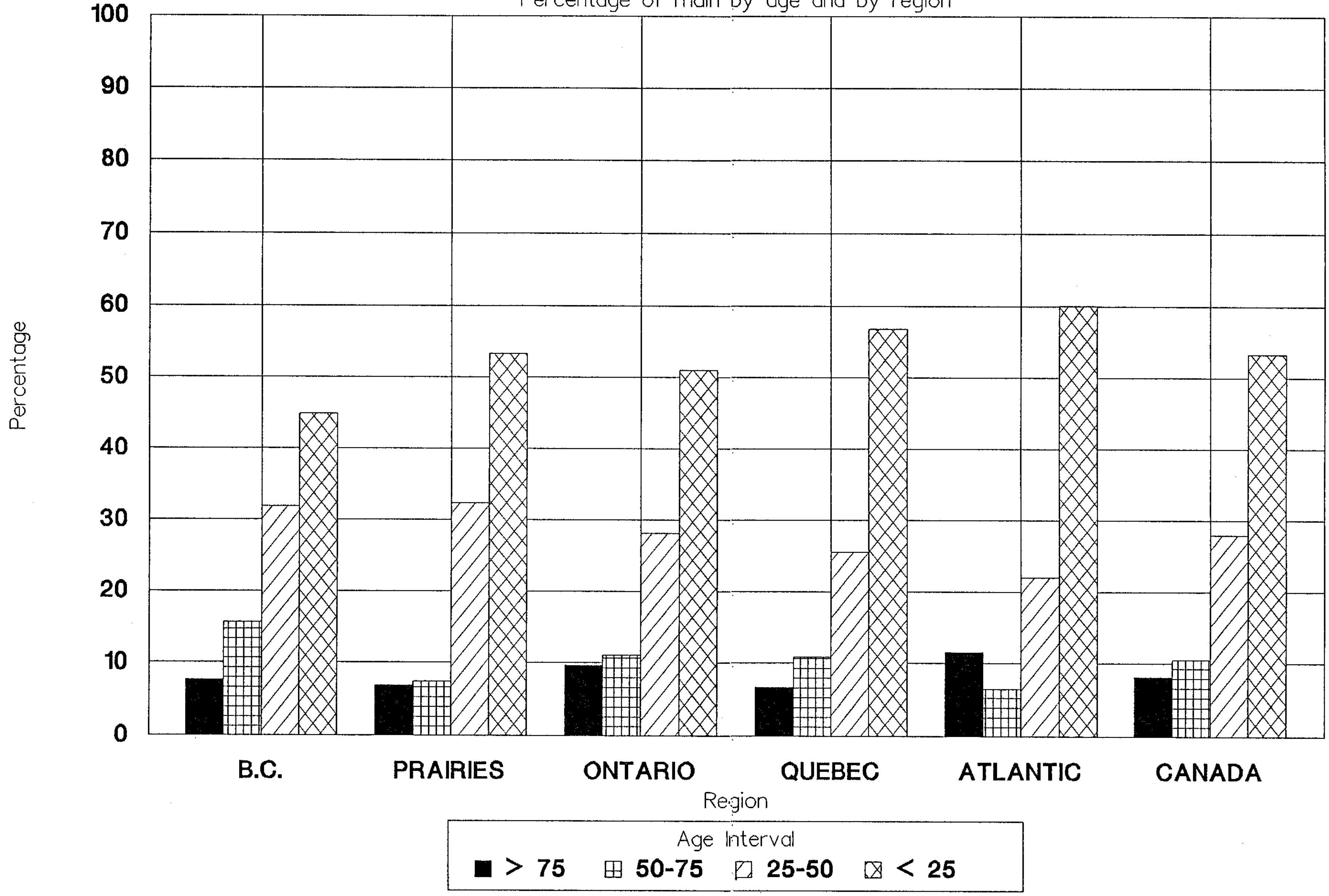
As can be seen from Figure 3.5, the majority of the Canadian system has been installed since 1951. Only about 23 percent of Canada's water mains were installed more than 40 years ago, and only 6 percent were installed more than 80 years ago.

As a percentage of their current system length, Atlantic Canada and Ontario contain the largest percentage of pipe greater than 75 years old (see Figure 3.6) and generally have the oldest systems (see Table 3.3). As expected, lower percentages of the oldest pipe are found in Western Canada, but perhaps surprisingly, the smallest percentage is found in Quebec. This may partly be due to the fact that historically the service densities have been high in Quebec, thus there is little "old" pipe left today. Also, the application of the relatively low densities found in B.C., Alberta, and Nova Scotia to Quebec communities may have resulted in a slight over-estimation of the current pipe length in Quebec, and intern the percentage of pipe which is less than 25 years old.

It is also interesting to note that B.C. holds the largest percentage of pipe which was installed between 50 and 75 years ago while maintaining the least amount of pipe less than 25 years old, indicating a large percentage of the community systems were initiated or expanded between 1916 and 1966 in the province. This gives B.C. the second oldest average systems length in the country (see Table 3.3) at 33 years, though this may

Figure 3.6: Canada's water works

Percentage of main by age and by region



be slightly exaggerated considering the large scale replacements in Vancouver during the 1960's (Bratton et al 1986) and considering that Vancouver contains a large percentage of the province's older water mains.

The large percentage of pipes installed nationally in the last 25 years corresponds to the rapid growth both in the population and in the funding from all levels of government aimed at providing expanded and better quality water distribution service. But still, 47 percent of the current systems are over 25 years old, meaning they are at or approaching an age where some major rehabilitation may be required.

On a pipe length basis, as expected, the longest lengths of old pipes are in Ontario and Quebec, which combined retain more than 64 percent of the country's pipes installed over 50 years ago (see Figure 3.7).

System age varies not only by province in Canada, but by size of community. Continuous records of pipe length by community and by year were only available through municipal statistics for Alberta, B.C. and Nova Scotia. Using this data, it can be seen in Table 3.4 that, as expected, the average age of the mains in the larger centres is older than in the smaller centres.

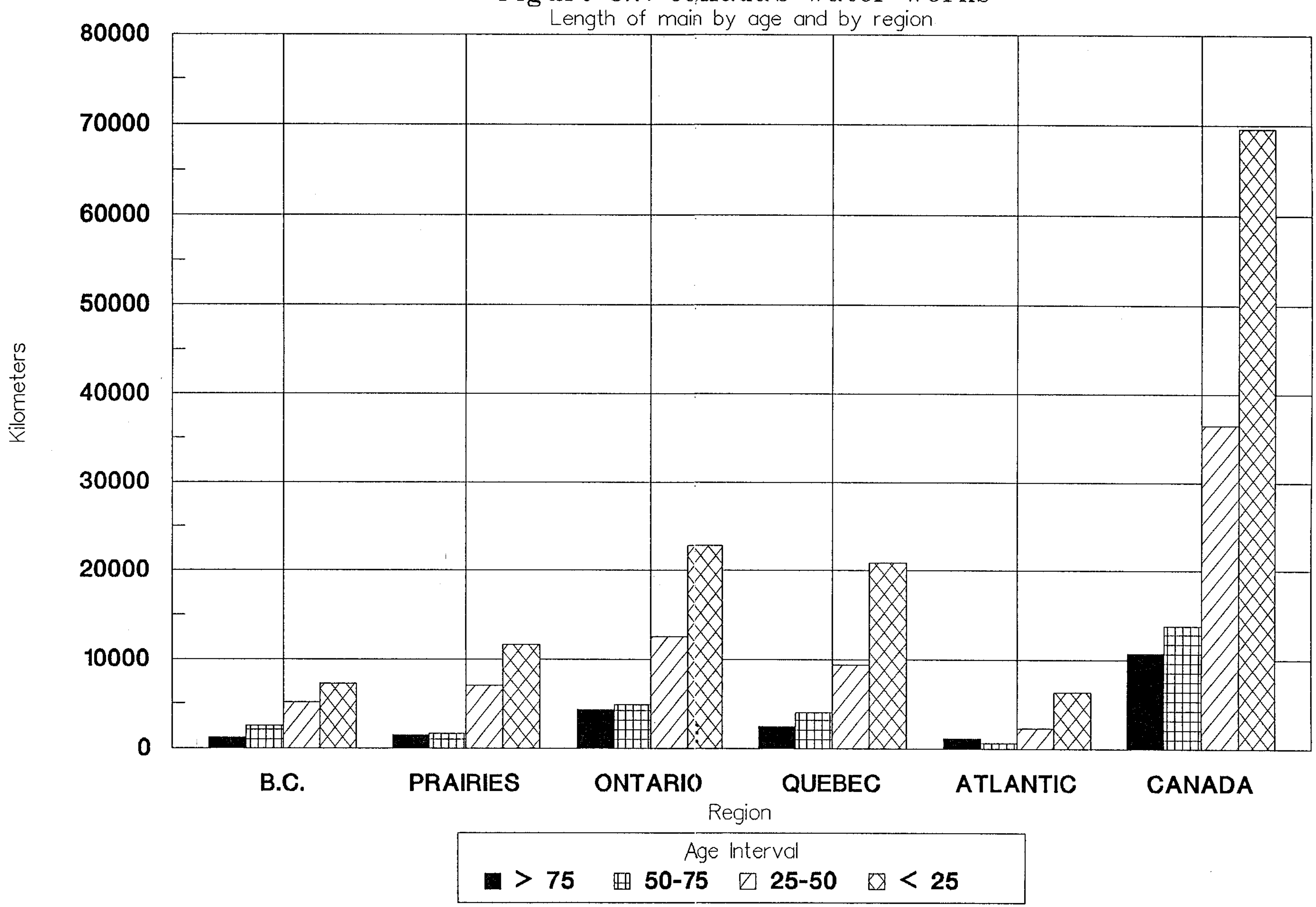
Table 3.4: Estimated age of distribution systems in selected provinces in 1991

	AVERAGE AGE (Years)			
COMMUNITY POPULATION (1988)	B.C.	ALTA.	N.S.	COMBINED
> 100,000	42	30	79 (*)	37
10,001 - 100,000	30	23	43	31
less or equal to 10,000	28	20	43	28
Provincial Average	33	25	46	32

* - Halifax is the only community in this category

Source: Derived from data base in Table 3.1

Figure 3.7: Canada's water works



However, the average age of the systems in the largest communities are typically only 10 to 15 years older than the smallest communities. This can partly be explained by the increasing growth in the larger centres, such as Calgary, Vancouver and Edmonton, which has resulted in a large amount of new mains being installed and a subsequent decrease in the overall age of the systems. Smaller communities have not experienced the degree of growth of the large cities and, as a result, a large portion of their current systems consist of the original pipe, though the age of this pipe is still younger than the oldest pipe in the large cities.

The average system age of the smaller communities also varies among the provinces. The smaller communities in Nova Scotia have average system ages anywhere from 15 to 20 years older than their western counterparts and there is no indication that major portions of the systems have been replaced. Referring to a recent study of the water systems in the Maritimes, MacLaren (1985) concludes that the worst problem areas are in small to medium sized communities which have never undergone major urban renewal nor experienced significant urban expansion.

It is also apparent that Nova Scotia maintains the oldest systems of the three provinces. As mentioned earlier, there seems to be some doubt as to the accuracy of the data for Halifax, though overall the anomaly does not seem to influence the results significantly.

3.2.3. Pipe Sizes

The size of a pipe is an important characteristics when considering the rehabilitation of a water main. In Canada, the majority of the pipes in any particular distribution system generally have diameters in the 100 mm to 300 mm range which are fed by transmission lines which usually range anywhere from 300 mm to over 1200 mm in diameter. Much of the data used in this section dates from 1961, but since design practise has not changed dramatically since then, the general information should be a quite reasonable estimate of today's situation. Probably the only major design change related to pipe diameter in the past thirty years has been a move away from small diameter pipes in the 100 mm and smaller range due to the need for increased fire flows.

As can be seen in Table 3.5(a), the larger a community the larger the pipes that can be found in its system. In 1961, nearly 93 percent of all the smallest communities surveyed had pipes no larger than 300 mm in diameter. In the largest communities, the largest sizes ranged from 550 mm to 1200 mm and up.

From Table 3.5(b) it can be seen that in most communities, the smallest pipe diameter was 100 mm, with only 22.5 percent of the communities having smaller mains.

From a sample of 78 small and 10 medium sized communities in the 1961 survey (MU 1961), it can be seen from Figure 3.8 that the most common pipe size is 150 mm, which comprises 55 percent of all the pipes, followed by 200 mm and 100 mm which represent 16 percent and 12 percent respectively. As noted earlier, the smallest communities contain very little large diameter pipes with only 12 percent of the pipe being larger than 200 mm, while in medium sized communities this value jumps to 21 percent. Although a breakdown for the largest sized communities is not available, it is reasonable to assume that the proportion of large diameter pipes is even greater.

Given these general trends, there can still be significant variations in the range of pipe sizes which seriously can affect system capacity, even among larger communities. In 1978, Surrey, B.C. had quite a large system serving approximately 130,000 people.

Table 3.5: Largest and smallest pipe sizes in Canadian communities in 1961

(A) Percentage of communities with largest pipe sizes by diameter:

Diameter (inches)	Size of Community: < 1,001	1,001-2,500	2,501-5,000	5,001-10,000	10,001-30,000	30,001-100,000	100,001+	Total	Diameter (mm)
48+						2.3	33.3	.8	1200+
27-47				1.7	3.3	25.0	40.0*	3.0	675-1175
22-24			.5	1.7	15.0	43.2*	26.7	5.7	550-600
18-20		.8	2.5	5.0	24.2	18.2		6.5	450-500
14-16		3.1	12.1	27.3	32.5*	9.1		13.9	350-400
12	8.7	12.2	26.3	33.1*	18.3	2.3		19.1	300
10	4.3	24.0	27.8*	20.7	4.2			19.0	250
8	30.4	43.7*	24.7	8.3	1.7			23.1	200
6	52.2*	13.0	5.6	1.7	.8			7.6	150
< 6	4.3	3.1	.5	.8				1.4	< 150
Total (%)	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
Sample Size	23	254	198	121	120	44	15	775	
Sample Pop.	39,000	527,850	777,700	956,300	2,264,730	2,400,546	5,451,724	12,417,850	
Sample km	61.2	1157.8	1452.6	1344.7	3199.7	3525.4	4866.4	15607.8	

(B) Percentage communities with smallest pipe sizes by diameter:

Diameter (inches)	Size of Community: < 1,001	1,001-2,500	2,501-5,000	5,001-10,000	10,001-30,000	30,001-100,000	100,001+	Total	Diameter (mm)
10-14		.4	1.0	2.5	2.5			1.2	250-350
8		2.4	2.0	.8				1.4	200
6	43.5**	24.4	24.2	22.3	18.3	9.1	20.0	22.7	150
4	34.8	47.6**	56.6**	54.5**	52.5**	63.6**	46.7**	52.3	100
< 4	21.7	25.2	16.2	19.8	26.7	27.3	33.3	22.5	< 100
Total (%)	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	
Sample Size	23	254	198	121	120	44	15	775	
Sample Pop.	39,000	527,850	777,700	956,300	2,264,730	2,400,546	5,451,724	12,417,850	
Sample km	61.2	1157.8	1452.6	1344.7	3199.7	3525.4	4866.4	15607.8	

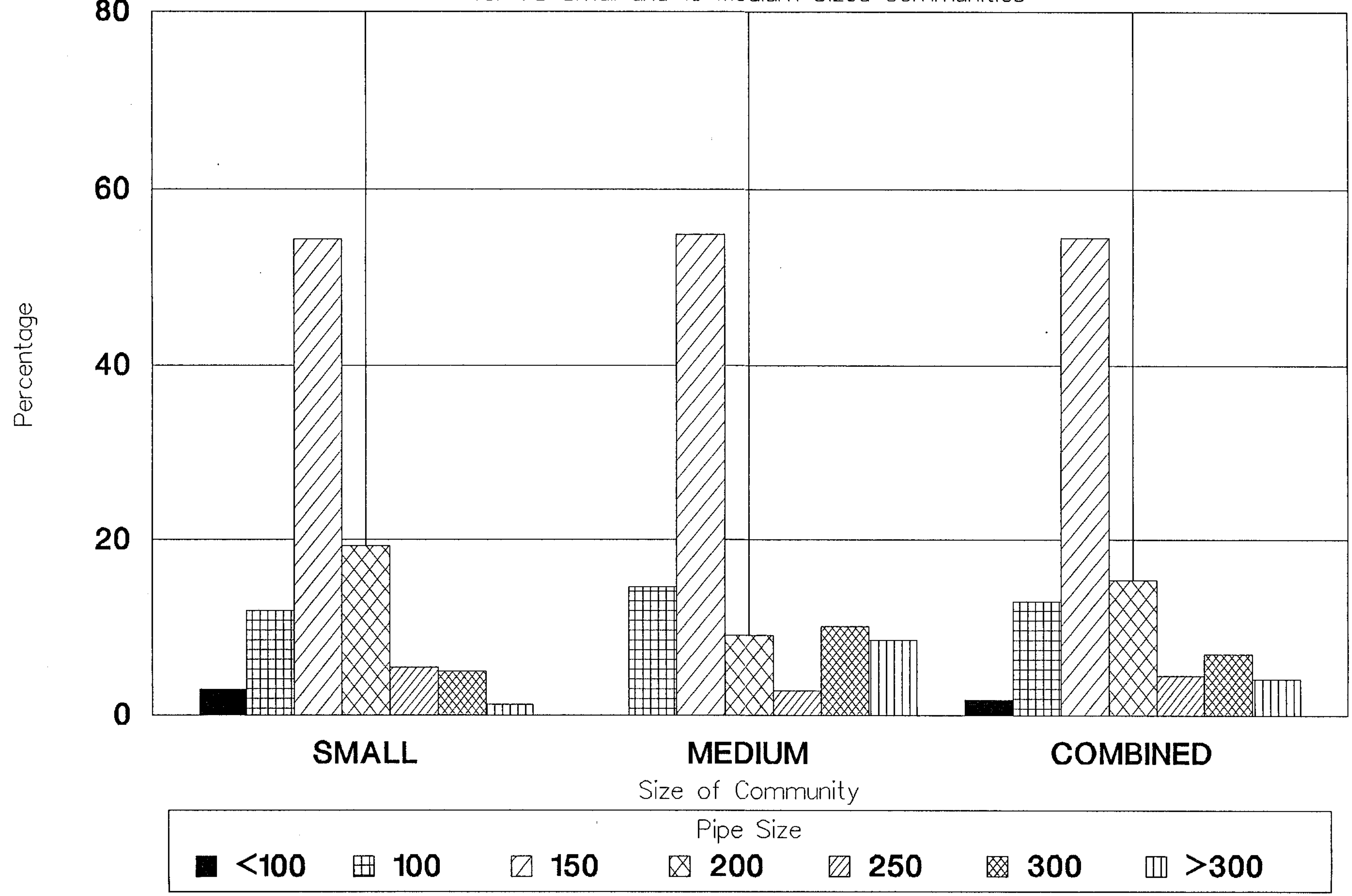
* - denotes the largest percentage of communities with this diameter as their largest pipe size
** - denotes the largest percentage of communities with this diameter as their smallest pipe size

Source: MU (1961)

The total 934 kilometres of mains had an unusually small percentage of large transmission sized mains (over 300 mm) and an unusually large percentage of very small diameter mains (under 150 mm) as can be seen in Table 3.6. The system was plagued

Figure 3.8: Canada's Water Distribution Systems

Diameter of Mains by Size of Community in 1961
for 78 Small and 10 Medium Sized Communities



by low pressure and flow. After significant public outcry and recent development pressures, the problem has been remedied by replacing many small diameter mains with larger ones (Lalani 1990). Many communities in Canada have not seen the development pressures that Surrey has and could today have serious capacity problems.

Overall, there is a predominance of small diameter mains in all communities. Approximately 80 percent of a typical system is made up of relatively small mains under 300 mm, with the figure closer to 90 or 95 percent in the smallest communities.

Table 3.6: Pipe sizes in Surrey, B.C. in 1978

Diameter	Percentage of System Length
< 100	7.25
100	21.95
150	46.35
200	12.37
250	1.09
300	6.95
> 300	4.03

Source: Surrey (1978)

The hydraulic basis by which pipes in Canada are sized is fairly straight forward. System design is based on maximum consumption rates, which can vary with the seasons, the day of the week, and the hours of the day. The seasonal peak is invariably in the hot summer months and the hourly peak is close to noon while the hourly minimum is in the early hours of the morning; typically, the maximum day exceeds the average day by 1.2 to 2.0 times while the maximum hour exceeds the average hour by 2.0 to 3.0 times (MacLaren 1985). While peak hour flows are important in the design, in a typical municipal system the critical design criteria is the provision of fire flows. The flow required for fire fighting purposes can be based on the community size, the land use density and type, and the fire fighting equipment and stationing. The Fire Underwriters Survey sets guidelines for municipal fire protection and the associated insurance ratings.

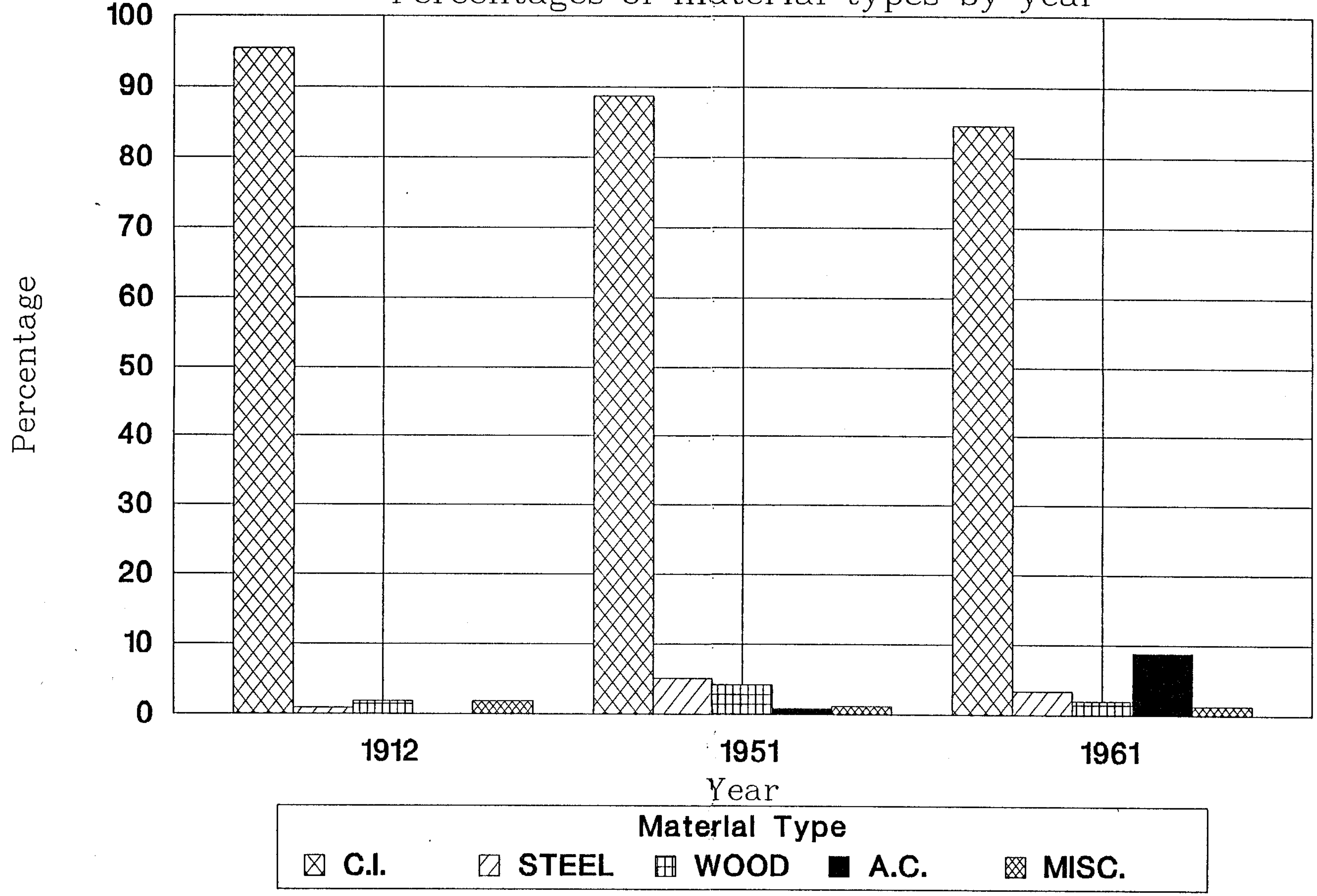
Unfortunately, as Canadian systems developed, economics and availability of materials often took precedence over the hydraulic design basis, thus in many communities the pipes installed have inadequate capacities to handle fire and in some cases even domestic flows. Typically, to handle fire flows a pipe must be at least six inches (150 mm) in diameter. As evident by this discussion, many communities have a significant amount of such inadequate pipe.

3.2.4. Pipe Material

It is unfortunate that extensive national information related to the more recent use of pipe materials is not readily available, especially since the use of new materials has evolved rapidly since 1961. The increased use of ductile iron (D.I.) and asbestos cement (A.C.) in the 1960's and 1970's and the more recent large scale use of P.V.C. and P.E. plastic pipes have dramatically changed the nature of new distribution works. The most recent national data source remains the 1961 Municipal Utilities publication. Although the information is significantly out of date with respect to current installations, it is still very applicable when considering current rehabilitation technologies which will generally be aimed at pipe installed prior to 1961.

Up to 1961, the major pipe material used in Canadian water mains was cast iron (see Figure 3.9). Up to 1951, materials such as steel and wood were primarily used for larger diameter transmission mains, along with smaller amounts of concrete and steel

Figure 3.9: Canada's water distribution systems
Percentages of material types by year



reinforced concrete which are included in the miscellaneous category of Figure 3.9. Also in this category are small galvanized iron pipes, usually less than 100 mm in diameter, which were common in some communities but not widely utilized. Wood was common as a pipe material in areas where the supply source was generally reliable and lumber available, mostly in B.C. with a small percentage in Quebec.

The development and initial use of new light-weight materials such as asbestos cement (A.C.) in the early 1950's displaced some of the traditional cast iron market. A.C. was first introduced in North America by Johns-Manville Corporation (U.S.A.) in 1929. It has been estimated that 2.5 million kilometres of A.C. pipe have been installed world wide, and in Canada A.C. has been used extensively since the early 1950's with 88.9 percent of the A.C. pressure pipe being located west of Ontario (Nebesar and Riley 1984). By 1961 A.C. made up almost 9 percent of the total system mileage, being especially popular in the corrosive soils of the Prairies (see Figure 3.9). In 1977, A.C. pressure pipe made up 18 percent of the new pipe market in Canada (Vagt 1980) and in 1980 made up 130,000 km or 13 percent of the total 1 million kilometres of water main in the U.S. (Nebesar and Riley 1984). If similar numbers apply to Canada, there could be as much as 13,000 km of A.C. pipe in the ground today, with over 11,000 km in Western Canada. Since the late 1970's, however, the use and manufacture of asbestos cement has diminished greatly with the wide spread use of plastic pipes, especially P.V.C. and to a lesser extent P.E., and with the recent public health concerns over asbestos in general.

Facing stiff competition from new materials, the iron pipe industry introduced ductile iron pipe which was both thinner, stronger, and more impact resistant than its more brittle cast iron predecessor. By 1967 ductile iron had all but replaced cast iron as a material for new pipes in cities such as Calgary (see Figure 3.10). Over the years, cities like Calgary and Vancouver continued the almost exclusive use of iron pipe in their systems. In Vancouver today, shallow bury depths and the high probability of third party damage require a material with high impact resistance such as D.I. (Bratton 1990). Unlike Vancouver, smaller communities in the Greater Vancouver area opted for a variety of newer materials over the years, including significant lengths of asbestos-cement as can be seen in Table 3.7.

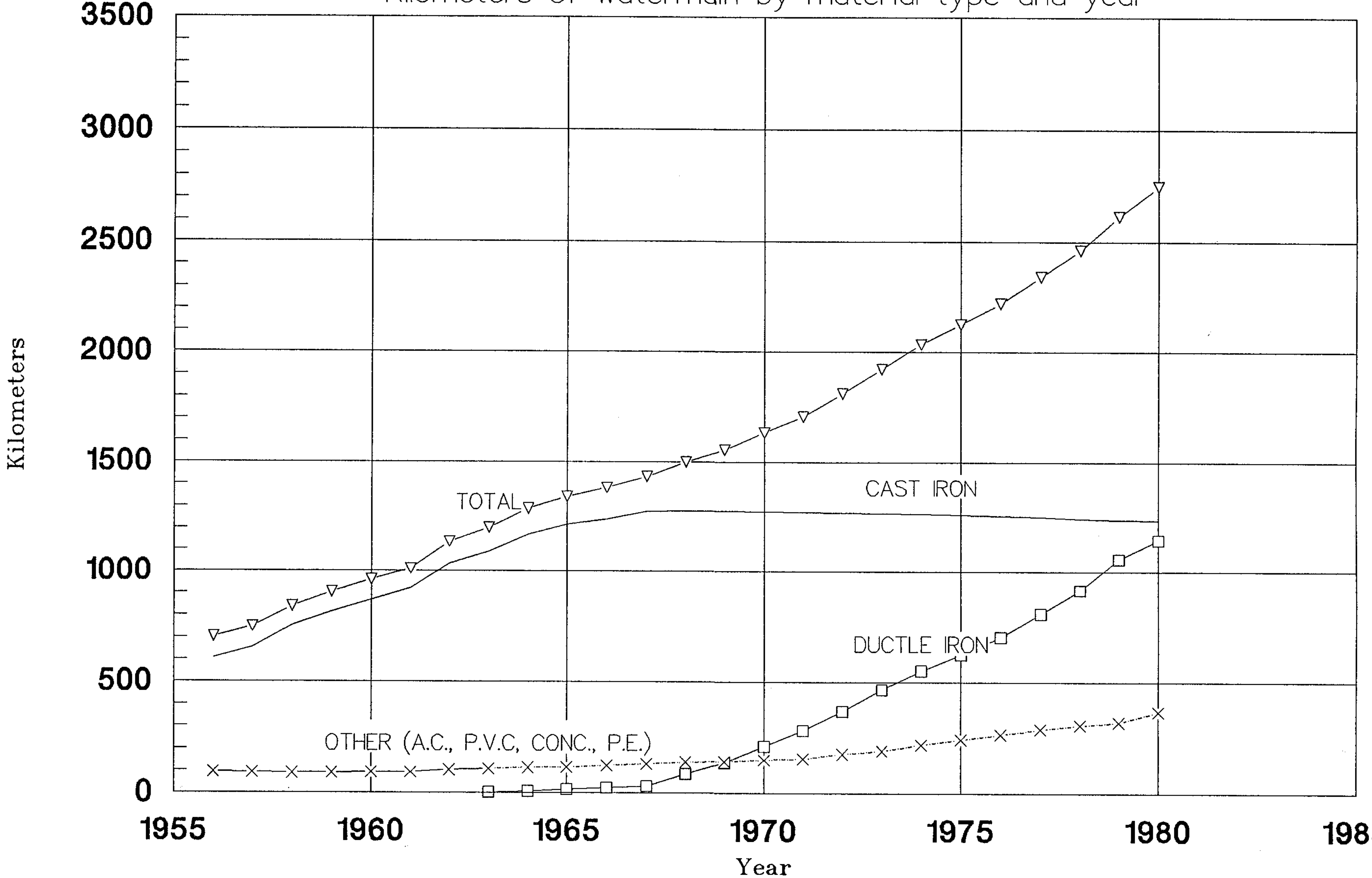
Table 3.7: Pipe material in selected B.C. utilities

MATERIAL	PERCENTAGE OF TOTAL SYSTEM LENGTH		
	Surrey (1978)	Burnaby (1991)	North Vancouver (1991) District *
C.I.	29.0	34.9	21.0
D.I.	29.3	19.9	20.0
A.C.	26.7	38.8	48.0
Steel	4.5	5.6	6.0
Plastic	0.3	0.1	0.0
Wood	2.0	0.0	4.0
Galvanized Iron	5.4	0.0	1.0
Concrete	1.8	0.0	0.0
Misc.	1.0	0.0	0.0
TOTAL	100.0	100.0	100.0
Total Length	934.3 km	665.7 km	392.0 km **

* - estimated material percentages from MacLean (1991)
** - estimated from 1988 B.C. Municipal Statistics

Sources: Surrey 1978; Robinson 1991; MacLean 1991.

Figure 3.10: Calgary's distribution system
Kilometers of watermain by material type and year



3.2.5. The Physical Environment

Just as the various systems in Canada vary with age, material type, and pipe diameters, so varies the physical environment to which the piped systems are exposed. Outside of the operational parameters such as pressure and pressure cycles which constantly strain the pipes over the years, the effects of aggressive distribution waters, aggressive soils, and frost penetration play a major role in determining the design and lifespan of the pipes.

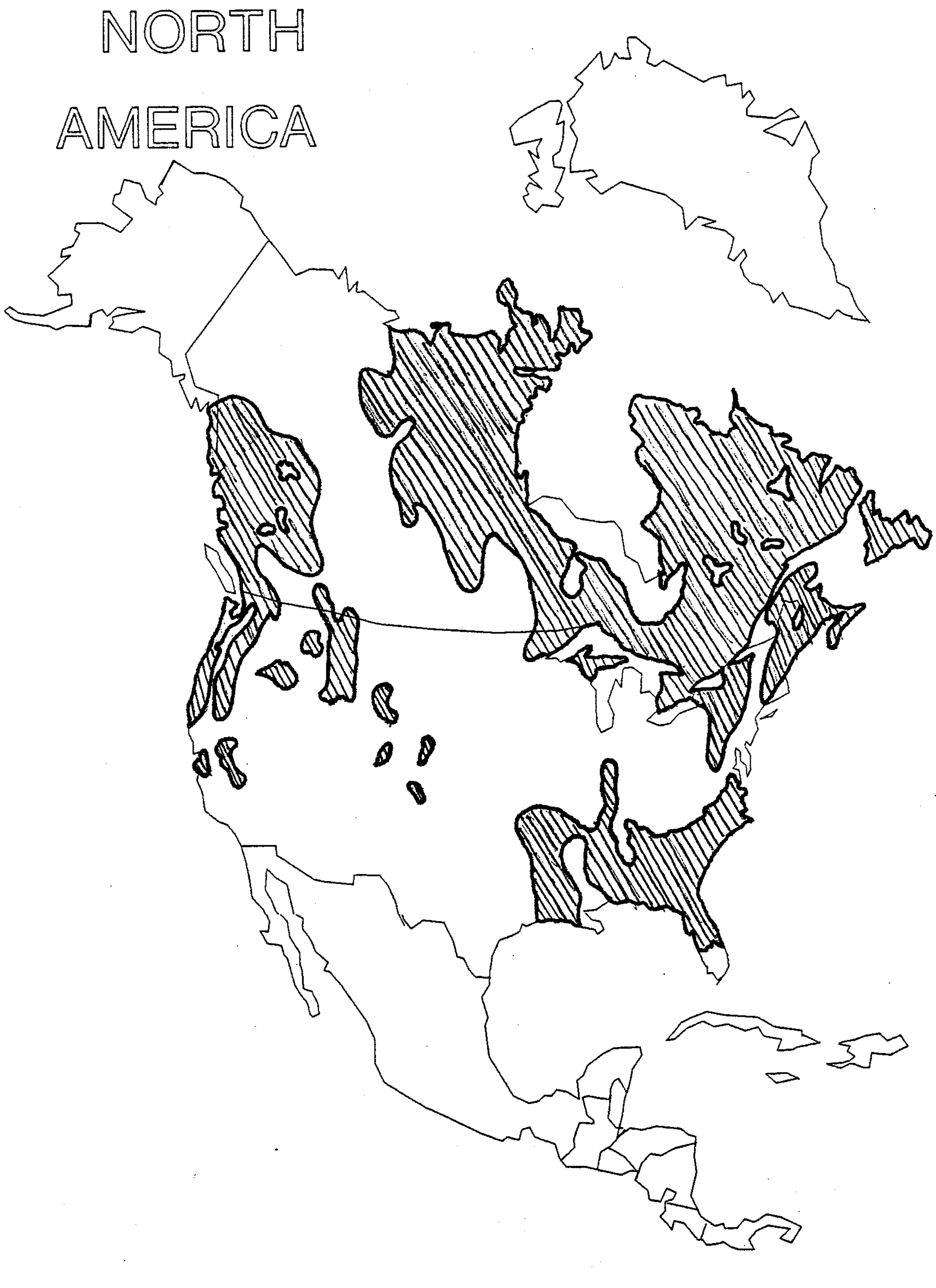
The acidification of the lakes and forests along the Canadian shield have raised national and international concern over the sulphur dioxide (SO_2) emissions from non-ferrous ore smelting operations and coal fired power plants, and nitrogen oxides (NO_x) from automobile exhaust and fuel combustion. East of the Saskatchewan/Manitoba border, over 4.5 million metric tonnes of SO_2 are released annually into the atmosphere, 49 percent of which are from Ontario and 24 percent from Quebec (Environment Canada 1986). Particles from these emissions react with water in the atmosphere and fall back to the earth as acid rain, depressing the pH of unbuffered soil and water bodies. The ten year Canadian Acid Rain Control Program aims to cut this level in half by 1994 with Quebec and Ontario commencing their respective emission control plans in 1985 (Environment Canada 1986).

The goal of the program is to reduce the annual acid deposition to less than 20 kilograms per hectare per year (18 lbs./acre/yr.), which is the level most lakes and rivers in Canada can tolerate without damage. The effects of acid rain have been well documented over the past ten years: it increases the acidity of lakes and streams to the point where aquatic life is depleted, it increases the acidity of shallow groundwater, it is suspected as one of the causes of forest decline, it erodes buildings and monuments, and is suspected of contributing to respiratory problems in people (Environment Canada 1986).

One of the effects of acid rain which receives little or no attention is the acceleration of corrosion in water distribution piping and the elevated levels of dissolved metals in the drinking water which may result. As can be seen in Figure 3.11, except for the Prairies, the Hudson Bay basin, and some relatively isolated areas, most of Canada is susceptible to the effects of acid rain. Sensitive areas are identified by mapping the bedrock with very little buffering capacity; buffering capacity being the capacity to neutralize acid solutions or to increase pH to the natural levels that prevailed in a hydrological system before the incidence of acid precipitation. Carbonate minerals (calcite, dolomite, siderite-rhodochrosite) provide the greatest buffering capacity per volume of rock, while clay-sized micaceous minerals provide the second greatest (Shilts 1981). Bedrock producing soils with quartz and feldspar rich silt, sand and pebbles are much more sensitive to acid precipitation. Thus the granitoid bedrock of the Canadian shield has very little buffering capacity while the limestones of the prairies have a high buffering capacity. Though the type of bedrock is the best overall indicator of soil sensitivity, some caution must be exercised as glacial transport of drift can distort the sensitivity patterns derived solely from the bedrock information (Shilts 1981).

While much of attention regarding pH depression of lakes and rivers due to acid rain has focused on eastern Canada where the major sources of sulphur dioxide and nitrogen oxides are located, the effects of acidic rainfall can be found in western Canada as well. Millette and Mavinic (1988) note that the pH of normal rainwater is approximately 5.5, while in Vancouver where the rainwater is normally acidic, the pH of drinking water is typically in the 4.5 to 5.7 range, well below the neutral pH 7 value.

Figure 3.11: Areas Sensitive to Acid Rain



The geology of the coastal region is such that the waters also contain very low concentrations of dissolved species, hardness and alkalinity being the main indicators of these. Thus, Vancouver is in a situation of aggressive waters with little buffering capacity. Millette and Mavinic (1988) found elevated levels of iron and copper in numerous tap water samples and considered the addition of lime as a solution. In Vancouver a large number of steel mains installed in the 1920's have had to be replaced due to excessive breaks and leaks caused largely by internal corrosion. In many of the communities surrounding Vancouver, asbestos-cement pipe has also been known to degrade due to the aggressive nature of the waters.

The immense size of Canada makes generalizations about climate and soil types nearly impossible. Typical frost penetration varies from nearly zero in Vancouver to 2.2 meters in Edmonton. In the north, where continuous permafrost exists, rather than measuring frost depth in the winter, thaw depths are measured in the summer (MOT 1973). A number of excellent sources are available for estimating the depth of frost penetration (MOT 1973, Canadian Geotechnical Society 1985) though the best records can usually be obtained from the local Environment Canada weather station.

Frost penetration has a huge influence on the design, cost, and maintenance of piped systems. In Alberta for instance, provincial design regulations are based on frost penetration and stipulate that all municipal water pipes must maintain at least 2.5 m of cover over the crown of the pipe, while in Vancouver, water lines are typically buried with only 1.0 m to 1.2 m cover, with such depths based on surface loads rather than frost penetration. Since a major part of the cost of pipelines is in the excavation and installation, the depth of cover is a big factor in overall installation and replacement costs. MacLaren (1983) notes that breakage rates in American cities, where frost penetration is much less, are much lower than comparative Canadian rates.

Table 3.8: Average frost penetrations in selected cities (1964-1971)

LOCATION	YEARS OBSERVED	AVERAGE FROST PENETRATION (m)	
		Asphaltic Concrete Pavement	Portland Cement Concrete Pavement
Fort Nelson, B.C.	7	3.3	
Smithers, B.C.	3	1.5	
Calgary, Ab.	5	1.9	
Edmonton, Ab.	6		2.2
Lethbridge, Ab.	3	1.2	
Regina, Sask.	7	2.0	
Saskatoon, Sask.	2	1.8	
Gimli, Man.	3	3.0	
Winnipeg, Man.	4	1.9	2.1
Lakehead, Ont.	4	1.5	
Ottawa, Ont.	3	1.6	
Toronto, Ont.	3	0.9	
Bagotville, Que.	4	2.1	
Montreal, Que.	3	1.4	
Quebec, Que.	3	1.3	
Fredericton, N.B.	3		1.7
Moncton, N.B.	3	1.2	
St. John, N.B.	4	1.6	
Halifax, N.S.	4		1.1
Sydney, N.S.	4	0.9	
Summerside, PEI	4		1.2
Gander, Nfld.	4		1.4
St. John's, Nfld.	4	0.7	
Hay River, NWT	2	3.6	
Yellowknife, NWT	2	4.3	
Whitehorse, Yuk.	7		3.2

Note: Depths are on snow cleared surfaces.

Source: Adapted from MOT (1973).

Soil types also vary across Canada and even within a given system can vary widely, especially systems which developed in river valleys or on flood plains where silt, clay, and gravel depositions vary widely and can therefor vary the corrosion rates on pipe materials. MacLaren (1983) notes that Winnipeg has had a tragic break record for more than sixty years due to the sulphate corrosion of the local gumbo clay on the original sand cast iron mains.

Calgary is also affected by extremely corrosive clay and silty clay soils and in the early 1980's implemented an extensive pipe replacement and cathodic protection program (James and Nq 1991). In 1978, the breakage rate in the City peaked at over 50 breaks per 100 km, or nearly 1,300 breaks system-wide. This represented a rate nearly twice that of the national average and five times the target break rate of 10 breaks per 100 km per year recommended by MacLaren (1983). Calgary's cathodic protection program concentrated on:

a) electrical isolation from electrical ground grids and unprotected water mains where practical,

b) electrical continuity of water mains to be protected,

c) use of dielectric coatings,

d) use of galvanic anodes for protection of coated and uncoated distribution mains,

e) use of rectified impressed current system for the protection of large diameter transmission main,

f) a monitoring system to check potentials of cathodically protected piping systems.

Since being implemented, the program has resulted in a reduction of the break rate by over one-half, with the City reporting 20 breaks per 100 km in 1990, or 583 breaks system-wide (James and Nq 1991). Using MacLaren's (1983) estimate of $3,000 per break repair, this translates into a saving of over $2 million a year.

Although research is continuing into the soil specific nature of water main deterioration (AWWA 1986a), the problems and the solutions will remain very site specific and will continue to be handled by each individual utility on the basis of experience and trial and error with a variety of existing methods.

3.2.6. System Demand

Both the level of service and the per capita water consumption have increased since the first systems were installed in Canada in the mid-1800's. Anderson (1988) notes that the first system in Quebec City was constructed in 1848 to accommodate a demand of approximately 166 litres per capita per day, but in 1924 a special commission had found the actual consumption was nearly seven times that amount or 1036 litres per day. Even today, Canada ranks among the highest per capita users of treated water (see Table 3.9), with an average per capita consumption of 360 litres per day (Tate and Lacelle 1987).

Table 3.9: Domestic per capita water use in selected countries

Country	Pumpage per capita per day (litres)
United States	425
CANADA	360
Sweden	200
United Kingdom	200
West Germany	150
France	150
Israel	135

Source: Tate (1990)

Tate and Lacelle (1987) estimate that in 1986, the average daily flow of all municipal water utilities in Canada serving populations over 1,000 totalled 12.4 million cubic meters (MCM). Over an entire year this represents enough water to fill Lake Ontario more than two and a half times (Canada World Almanac 1990).

Of this water, Tate and Lacelle (1987) estimate that 40 percent is used for domestic purposes, 34 percent is used for commercial, institutional or industrial purposes and 26 percent is unaccounted for.

On average, leakage and waste accounts for at least 20 percent of unaccounted water (Tate and Lacelle 1987), or more than 5 percent of total daily flows. Tate suggests this to be further evidence of the need for major system renovation (Tate 1990).

Tate and Lacelle (1987) note that only a small fraction of domestic water is used for drinking and cooking, with over 70 percent either used in toilets or on the lawn (Table 3.10).

Table 3.10: Municipal water use in Canada

A) MUNICIPAL END USES:

Major End Use	Percentage of Total Pumped
Domestic	40
Commercial/Institutional	16
Industrial	18
Losses/Unaccounted	26

B) DOMESTIC END USES:

Domestic Use	Percentage of Total Domestic Use
Drinking/Cooking	5
Toilet	40
Lawn Watering	30
Bathing/Personal	15
Laundry	10

Source: Tate (1990)

Only 1.34 litres of water per day is required per person per day for drinking (Hickman 1984, MacLaren 1985), which is only 0.4 percent of the average per capita domestic water usage of 360 litres per day (Tate 1990).

3.2.6.1. Community Demand Profile

Based on recent data obtained from the Inland Waters Directorate (IWD 1990), water consumption rates vary among different sized communities in Canada. From the data, the 30 largest communities in Canada have the lowest per capita domestic water consumption rates which are on average 15 percent below the calculated national average of 351 litres/day/capita (see Table 3.11). Small and medium communities both tend to have similar rates which are typically more than 20 percent above the national average.

Table 3.11 Domestic per capita water use in Canadian communities in 1989

Population	Communities Surveyed	Per Capita Consumption (l/d/cap) High	Low	Average
100,000 +	30	475	95	292
10,001 - 99,999	244	1727	93	402
0 - 10,000	817	2749	36	434
CANADA	1091	2749	36	351

Source: IWD (1990)

Based on total water usage, there is no significant difference among the various sized communities. The difference between domestic and total water usage accounts for commercial, institutional, industrial, or other consumptive uses which occur in a community. As can be expected and as evidenced by Table 3.12, in smaller communities where the population base is small and there may be a single large industrial user of water, the occurrence of very large "per capita" total consumption figures will be more common than in the larger communities.

Table 3.12: Total per capita water use in Canadian communities

Population	Communities Surveyed	Per Capita Consumption (l/d/cap) High	Low	Average
100,000 +	30	1310	368	698
10,001 - 99,999	244	2878	155	680
0 - 10,000	817	6836	40	668
CANADA	1091	6836	40	688

Source: IWD (1990)

The percentage of surveyed communities which consume water at a significantly higher rate than the national average can be seen in Table 3.13. Approximately 44 percent of all communities in Canada use domestic water at rates at least 15 percent over the national average. On a national scale, this could amount to over 1,200 communities, nearly all of which are small and medium sized.

Table 3.13: Occurrence of domestic water use rates in Canadian communities in 1989

Consumption (l/d/cap)	Communities Surveyed	--Percentages of Canada's Total-- Communities	Popn.	Flow
0 - 200	115	11	18	12
201 - 400	497	45	55	54
401 - 2750	479	44	27	34
CANADA	1091	100	100	100

Source: IWD (1990)

3.2.6.2. Regional Demand Profile

The same data set as used for the communities can also be used to derive regional consumption trends. As can be expected, average water consumption rates vary from province to province, but as can be seen in Table 3.14 the lowest consumption rates are in Ontario and on the Prairies, while the highest rates are in Quebec and on the two coasts.

The highest per capita water usage occurs in New Brunswick, Quebec, Newfoundland and B.C. where supplies are abundant and a large volume of municipal water is supplied to industrial and other processes. Lowest per capita usage occurs in Ontario, P.E.I. and on the Prairies where good supplies tend to be more limited. The low values for Ontario are undoubtedly due to the heavy weighting of urban areas such as Toronto, Hamilton, and Ottawa which have quite low per capita consumption rates.

Table 3.14: Provincial per capita water use in Canada in 1989

Province	Consumption (l/d/cap)		Percentage of National Flow	
	Total	Domestic	Total	Domestic
Newfoundland	729*	515*	1.4	1.9
P.E.I.	525	221	0.1	0.1
Nova Scotia	646	357*	1.6	1.7
New Brunswick	1136*	514*	3.1	2.8
Quebec	844*	420*	32.9	32.2
Ontario	605	276	34.1	30.5
Manitoba	491	370*	2.8	4.1
Saskatchewan	591	317	2.7	2.8
Alberta	585	314	8.8	9.3
B.C.	722*	429*	12.3	14.4
Yukon	737*	414*	0.1	0.1
N.W.T.	551	327	0.1	0.1
CANADA	688	351	100.0	100.0

Note: * - indicates higher than national average

Source: IWD (1990)

Table 3.15: Regional per capita water use in Canada in 1989

Region	Consumption (l/d/cap) Total	Domestic	Percentage of National Flow Total	Domestic
Maritimes	845*	451*	6.2	6.5
Quebec	844*	420*	32.9	32.2
Ontario	605	276	34.1	30.5
Prairies	565	327	14.3	16.2
B.C.	722*	429*	12.3	14.4
Territories	642	370*	0.2	0.2
CANADA	688	351	100.0	100.0

Note: * - indicates higher than national average
Source: IWD (1990)

3.2.7. <u>Water System Staffing Levels</u>

While the maintenance of water distribution systems has remained at adequate levels, there is still evidence of gradually reduced staffing levels over the years. While some of the reductions could be attributed to more efficient maintenance and repair techniques and improved pipe and installation technology, the decrease in staff levels still exhibits a shift away from management of infrastructure systems.

According to Statistics Canada in their annual publications of <u>Municipal Government Employment</u> and <u>Local Government Employment</u>, the total number of people employed by local government, in communities with more than 10,000 people, more than doubled during the period from 1962 to 1984, increasing from 107,294 to in excess of 244,000. Over the same time, water systems expanded enormously with the total length increasing by more than 2.5 times. Yet during this period, the number of people employed in the water works departments increased by just over 10 percent, going from 6,989 in 1962 to 7,738 in 1984. This is further indication of the shift in local government's support over the years away from basic infrastructure needs in order to serve the ever increasing demands of expanded social services.

CHAPTER 4: WATER MAIN DETERIORATION

4.0. Overview

In order to effectively deal with the deterioration of a water systems, a good understanding of what deterioration is, the mechanisms responsible for it, and the available procedures a utility may implement to mitigate it are invaluable. This section will introduce the common indicators of water main deterioration, the major causes of it, the mechanisms associated with it, and the techniques used to deal with it.

Although every pipe in the ground has been designed to withstand such loadings within a given environment, the design process by nature is one involving a number of assumptions and general principles to come up with one specific design which must satisfy a wide range of environmental loadings developed. With pipelines this is especially the case. It is economically impractical to constantly change the pipe characteristics to accommodate every condition along a pipeline's total run. A typical pipe design will specify only one or two materials each with specific wall thicknesses and diameters, and some factor of safety to accommodate the broad range of localized environmental loads to which a high level of uncertainty exists.

This process of general design to accommodate specific local loadings works quite well, but not all consequences can be foreseen and not all conditions adequately predicted, especially when long periods of time are involved in the operational life of a pipe. Thus failures of the pipeline in the form of breaks or leaks will always occur, with the frequency of occurrence the indicator of a successful design. The design process involves combining imperfect information and an imperfect understanding of all the physical mechanisms to come up with the best design for the lowest possible cost. In such a process there is a trade-off between uncertainty and economics. It would is possible to design a pipe which could potentially last 300 years without a break, but the economics would prohibit such a design. Thus a pipe is inherently designed to deteriorate and eventually wear out.

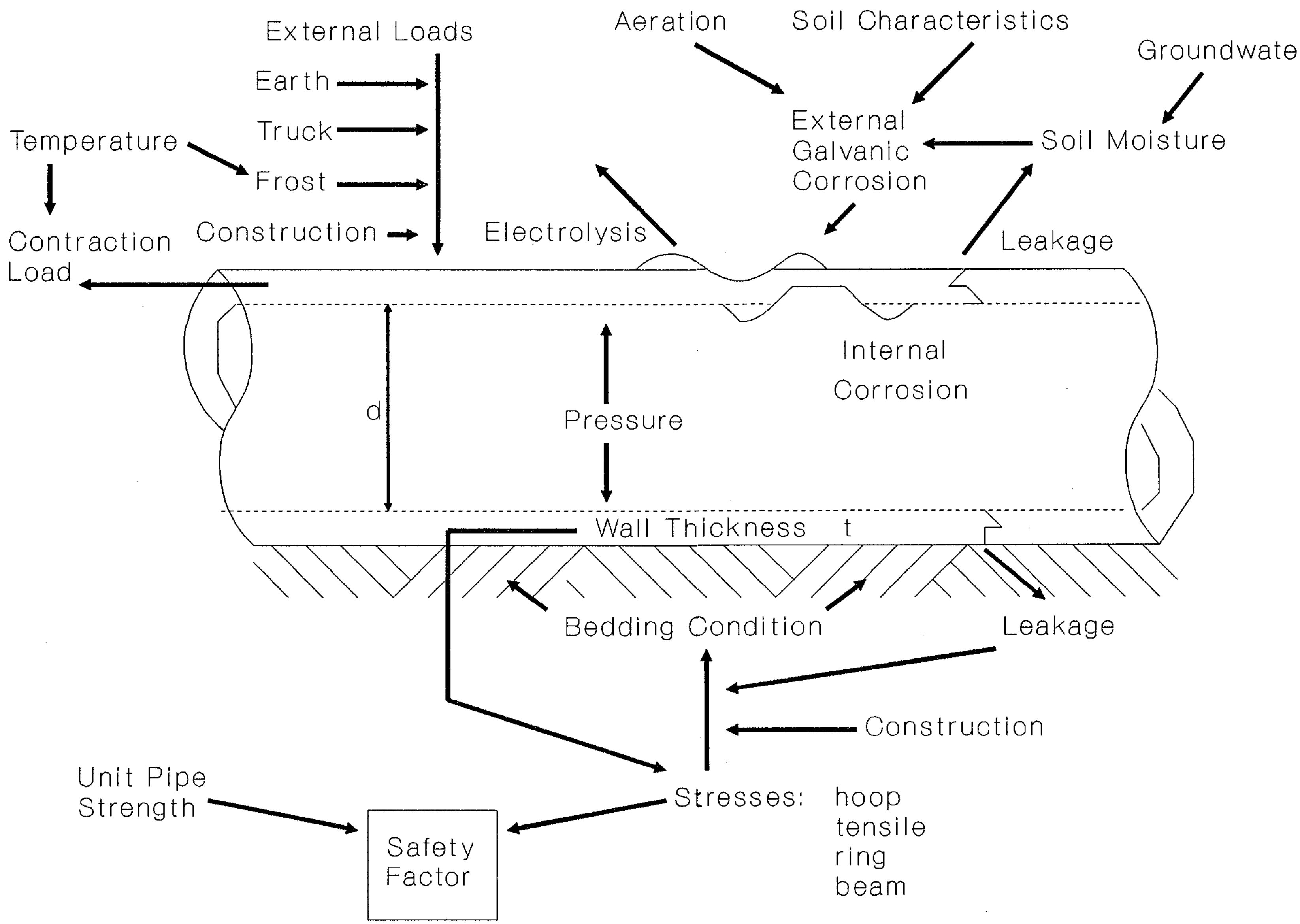
4.1. Defining Water Main Deterioration

The response of a pipe to its environment is dependent on a wide variety of complex, interacting influences. Soil conditions, pipe material, pipe geometry, external loadings, internal pressures, temperature, and construction all play a part in the life of a pipe as can be seen in Figure 4.1. Unfortunately, not all influences can be predicted with a great deal of certainty and many conditions can change radically to affect the performance of a pipe. The situation is further complicated by the fact that there is not an easily distinguishable point in time when a pipe can be considered to have succumbed to its environment and needs replacing due to failure.

The deterioration of a water pipe is not a discrete phenomenon, but rather one of varying degrees. In general, a pipe is designed to carry a certain quantity of water from one point to another, and any time the pipe fails to do this can be considered a "failure". Based on this simplistic definition, a pipe break is most often associated with failure since a break disrupts flow. But the occurrence of one break is not sufficient to merit replacement of the entire water main.

The determination of when to replace must incorporate some type of criteria which defines when a main has truly "failed" to serve its intended purpose. This is typically defined as that point in time where it becomes more economical to replace a water main rather than to continue its operation or the point in time when the risk in maintaining an increasingly unreliable pipe becomes too great. When these

Figure 4.1: Conceptual model water main structural condition



determinants are used, a number of structural and performance factors, other than just breaks, can be introduced into the formula which determines the replacement time.

From a structural perspective, the common indicators of deterioration are main breaks and leaks. The costs associated with continued operation include the costs associated with repairing both the breaks and any detected leaks plus the costs associated with the water lost due to the detected breaks and leaks, as well as the undetected leaks. For discussion purposes, a leak and a break are distinguished in that a break interrupts flow and is therefor easily detected by large volumes of water appearing at the ground surface. It usually does not result in significant water loss over time since it is often a short-term event. In contrast, a leak does not interrupt the flow and if it is a slow leak or does not surface due to bedding or sub-surface conditions (gravel beds or underground streams), it can often remain undetected and result in significant water losses over time.

Because of the difficulty in locating many of the small, less detectable leaks, many utilities do not concentrate on remedying leakage problems in their systems, but rather chose to base pipe repair and replacement on the increased costs due to emergency repair events caused from breakage. Undetected leaks remain largely ignored, and though each may be small, all together they can represent sizeable water and revenue losses over time.

4.2. Stresses on a Pipe

The degradation of a pipe's physical properties depends largely on the interaction of the pipe material with its surrounding environment over time. The interaction can result in changes to the geometric or material properties of a pipe. Geometric changes can include pitting or thinning of the pipe wall, or extreme deflections which can cause loss of seal at joints. Changes in material properties usually result in a loss of strength through a corrosion or ageing process which results in a chemical change of the material, a hardening or softening of the pipe wall, or a leaching out of constituent materials. In any case, the mechanical properties of the pipe are changed and the ability of the pipe to withstand loads is reduced. Such degradation is not only limited to the pipe, but can affect the joints and the various appurtenances such as the service connections, the valves, and the hydrants.

A number of authors have noted a wide variety of interpretations by utilities with respect to a what is considered a pipe "failure" and have commented that there is a pressing need to adopt standard main repair definitions and reporting procedures to help monitor and compare experiences (AWWA 1986a). Some utilities distinguish between "break" and "leak" repairs, while some aggregate the two, while others record "maintenance events" which can include any repairs on a pipe. For the purposes of this discussion, the designations adopted by the AWWA (1986a) will be used.

Using the AWWA definition, any loss of water associated with the degradation of these material properties is considered a leak. A leak can be through corrosion holes or at joints or through a macroscopic discontinuity (ie. a break). In this sense a break is merely one type of leak. A break is accompanied by a water loss which approaches the actual flow in the pipe, while smaller leaks lose so little water they cannot be distinguished from normal demands. Breaks are especially critical to the effective operation of system as they disrupt service, reduce fire-fighting capabilities, damage property, pose a public health threat, and can be costly to repair.

The AWWA designates four types of leaks: a main leak, a service leak, a valve leak, and a hydrant leak, with a main break and a joint leak considered special types of main leaks. The resulting set of definitions then apply:

Leak Repair: all actions taken to repair leaks in mains, line valves, hydrant branches, and service pipes;

1) Main Leak: all problems which lead to leakage of water from the main (including joint leaks, holes, circumferential breaks, longitudinal breaks, defective taps, split bells and not hydrant, service line or valve related leaks),

   a) Joint Leak: a loss of water from the joint between adjacent main sections and not a structural problem, but a separation of the main sections caused by expansion and contraction, settlement, or movement of joint materials because of pressure or pipe deflection,

   b) Main Breaks: structural failure of the barrel or bell of the pipe due to excessive loads, undermining of the bedding, contact with other structures, corrosion, or a combination of these. There are four types of main breaks:
      - circumferential
      - longitudinal
      - holes from corrosion or pressure/blowout
      - split bells including bell failures from sulfur compound joint material

2) Valve Leak: leaks at valve flanges, valve bonnets, or valve bodies,

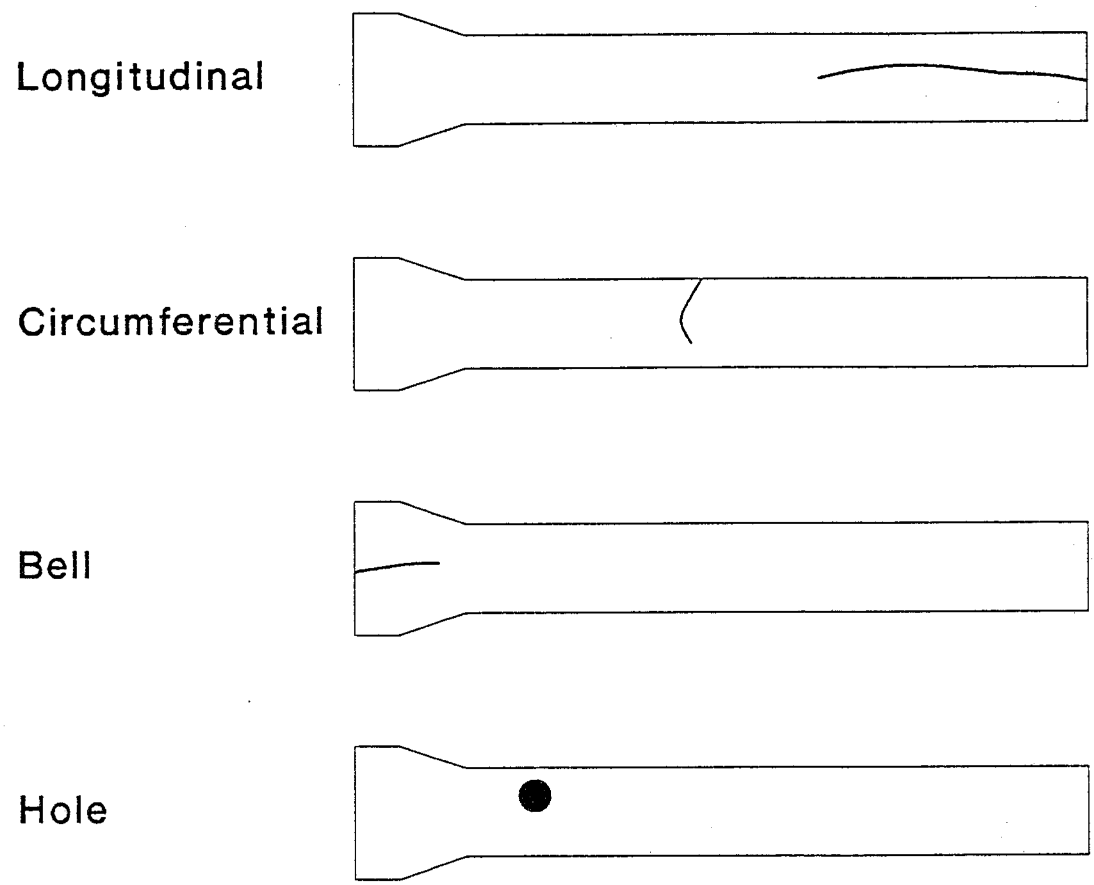
3) Hydrant Leak: leaks at hydrant branch lines, hydrant valves and hydrant barrels,

4) Service Leak: leaks at taps, corporation stops, service pipes, and curb stops.

The four types of main breaks are illustrated in Figure 4.2.

The nature and characteristics of main breaks merits a more detailed discussion. The type of environment in which a pipe is laid is probably the single most important factor which contributes to its deterioration over time. A pipeline is not too different from any other type of structure; it experiences both live loads and dead loads, it has unique structural properties, and a good foundation is an integral part of the entire structure. The degree of deterioration may or may not contribute to the occurrence of a

Figure 4.2: Types of water main breaks



Break Type	Stress Axis	Structural Causes
Longitudinal	Transverse	Excessive Ring Loads Internal Pressure
Circumferential	Longitudinal	Thermal Contraction Beam Failure Internal Pressure
Split Bell	Transverse	Lead Substitute Joint Expansion

Source: Adapted from AWWA 1986

break, depending on the nature of the loads. Assuming a pipe has been properly designed to withstand any anticipated loads, there are three main scenarios which can produce failures:

1) the intensification of anticipated loads above the load carrying capacity of a pipe
2) the presence of unanticipated loads above the load carrying capacity of a pipe
3) the degradation of the pipe's physical properties which decreases the load carrying capacity of a pipe.

The combination of the above three scenarios generally indicates the probability of a break. In general, if a pipe has not experienced loads greater than its design capacity and has not undergone significant deterioration, chances are it will not produce a break. If a pipe has not experienced loads greater than its design capacity, but has incurred some deterioration, chances are it may form a leak, but unless the deterioration is excessive, will probably not form a break. If a pipe is exposed to excessive anticipated or unanticipated loads, chances are good it will develop a break, and will be greater if the pipe has been weakened through deterioration.

The loads typically anticipated in a pipes design include the dead load due to the earth pressure, the live loads due to traffic, the internal loads due to pressure and in recent years, the internal loads due to waterhammer. The loads and the effects of the loads can be increased over the life of a pipe. For instance, the increase in the weight or volume of large trucks over the years can increase the vehicle loads and the number of cycles respectively, the loss of bedding due to leaks, washout, or settlement can increase the bending moments induced by the earth pressure, and the improper operation of a system can increase the operating and water hammer pressures.

While these loads may be the most obvious and the most easily determined in design, there are a number of other loads which can act on a pipe but which can not be predicted with a high degree of certainty due to the complexity of the underground environment, especially over the lengthy life of a pipe. Cyclic loadings due to frost, long-term loads induced by soil movement, and intense short term loads due to construction equipment impacts and earthquakes can result in both localized or more wide-spread failures. These loads have typically been accounted for by the designers choice of an appropriate factor of safety, but changes in standards and technical knowledge over the years have resulted in a wide variety of pipes with an equally wide variety of resistances to such loadings. The effects of such loads are highly variable and difficult to predict, as they can act in combination and largely depend on the integrity of the pipe at any particular time.

A pipes ability to resist such loads can be reduced by corrosion or erosion which act to degrade its physical and material properties. Internal corrosion from aggressive waters or external corrosion from corrosive soils or stray current can cause both localized reductions in wall thickness, which is common to metal pipes, or an overall reduction in pipe wall thickness, which is common to both asbestos-cement and metal pipes. Internal erosion of the pipe wall due to high velocity water can also cause localized weak spots. The effects and rate of such degradation vary with material type and the environmental conditions.

In McIntyre and Elstad's (1987) survey of Ontario water systems, there were four major causes of watermain failures: frost, construction methods, material failure and ground movement (see Table 4.1).

Table 4.1: Reported reasons for water main failures in Ontario

CAUSE	MECHANISMS INCLUDED	PERCENTAGE REPORTED
Frost	Frost, Frost Heave, Frost Jacking, Other Temperature Effects	28.9
Construction Methods	Rocks in backfill, Poor tamping of bedding, Adjacent Construction	19.3
Material Failure	Corrosion (11.7 %), Age (8.2 %)	19.9
Loss of Bedding	Ground Movement (erosion, differential settlement), Poor Bedding	11.0
Other or Unknown	Varies	21.0
TOTAL		100.0

Source: Adapted form McIntyre and Elstad (1987)

Pipe deterioration is directly influenced by the stress regimes encountered. The variety of stresses which a pipe must resist can be seen in Figure 4.3. Bending stress may be induced from soil movements or surface vehicle impacts and is highly dependent on pipe geometry. Axial stress may be induced by temperature changes and is influenced largely by the properties of the joints. Shear stress may be induced by differential soil movements and is especially important when pipes are connected to rigid structures. Ring loads may be induced by changes in external soil pressures or internal water pressure fluctuations and depend largely on the operations in and around the pipe.

The major factors influencing pipeline failures are numerous and have been summarized into four major categories by Shamir and Howard (1979):

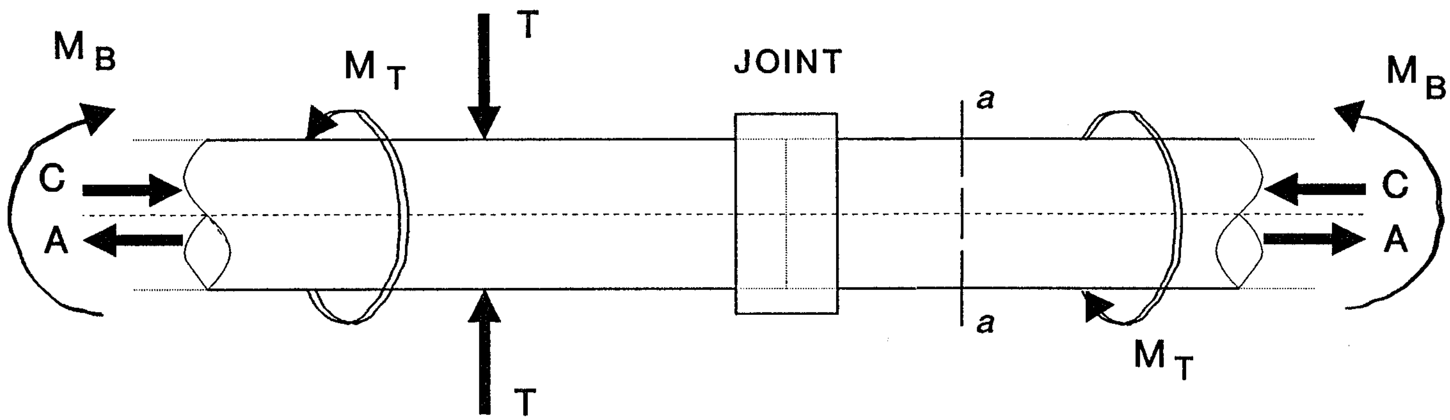
1) the type of environment in which the pipe is laid and the associated loads, including the corrosiveness of the soil, frost and heaving, external loads;

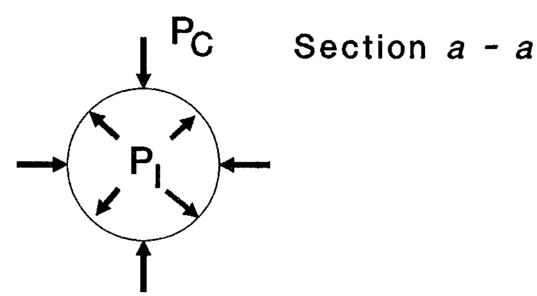
2) the characteristics of the pipe, connectors and other equipment, including quality, age, size, and type;

3) the quality of the workmanship used in laying the pipe;

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

Figure 4.3: Stresses on a buried water main





M_B : bending moment due to floating stress or overburden

M_T : torque or torsion

T : shear stress

A : axial tensile stress

C : axial compressive stress

P_I : internal overpressure

P_C : internal depression or external overpressure

Source: Adapted from Moruzzi (1987)

The reasons for a pipe break are diverse and can come from a number of sources, each of which produces a unique combination of stress conditions. Table 4.2 outlines some of the major causes which contribute to a break and the stresses each can induce.

There are four break types which are common to these stress regimes, as can be seen in Figure 4.4. The relative ability of a pipe to resist a particular stress regime is largely dependent on the pipe's material, characteristics, the joint type, and the pipe geometry. Moruzzi (1987) compares the relative resistance of various pipe material/joint combinations using a scale from 0 to 10, where 0 represents the least resistance and 10 represents the most (Figure 4.5). While the comparison is based on the physical properties of new pipes and not the actual field measured performance, it still provides a useful base for discussion.

Table 4.2: Stresses associated with common causes of breaks

REASON FOR BREAK INDUCED	EXAMPLE OR SOURCE	POTENTIAL STRESSES
Violent movement of the soil	earthquake, landslide, building collapse, war	M_B, M_T, T, A, C, P_C
Slow movement of the soil	subsidence, road settlement, pipe settlement	M_B, T, A
Excessive transmission of direct surface loads	poor soil thickness above pipe, heavy vehicle impacts	M_B, T, P_C
Low temperatures	poor pipe protection, cold winter water temperatures	P_I, A
Water Hammer	overpressure or depression from various sources	P_C, P_I, A,
Road and adjacent works	soil disturbed over, under, and/or adjacent to pipe.	M_B, M_T, T, A, P_C

Source: Adapted from Moruzzi (1987)

Figure 4.4: Degree of resistance to various types of stress

		TYPES OF WATER PIPES AND JOINTS											
		GREY C.I.		D.I.		A.C.	STEEL		P.V.C.		P.E.		F.R.P.
		PRES	FLNG	PRES	FLNG	SLVE	WELD	FLNG	PRES	SQEZ	SLVE	WELD	SQEZ
TYPES OF STRESS	M_B	5	6	6	6	4	10	9	6	5	7	10	8
	M_T	6	5	6	6	6	10	9	5	5	6	6	6
	T	5	5	9.5	9.5	4.5	10	10	1.5	1.5	1.5	1.5	2.5
	A	0	6	0	9	0	10	9	0	1.5	0	1.5	2.5
	C	7	10	7	9	4.5	9	9	1	1.5	1	1	1.5
	P_I	7.5	8	9	10	8	10	10	7.5	8	7.5	8	8.5
	P_C	7.5	10	5.5	5.5	9	3	3	4	4	4.5	4.5	5
	TOTAL	38	50	43	60.5	36	62	59	25	26.5	27.5	32.5	34

Source: Adapted from Moruzzi (1987)

Figure 4.5: Degree of resistance to various failure types

	TYPES OF WATER PIPES AND JOINTS											
	GREY C.I.		D.I.		A.C.	STEEL		P.V.C.		P.E.		F.R.P.
	PRES	FLNG	PRES	FLNG	SLVE	FLNG	PRES	PRES	SQEZ	SLVE	WELD	SQEZ
VIOLENT MOVEMENT OF THE SOIL	29.5	42	34	45	28	52	49	17.5	18.5	20	24.5	25.5
SLOW MOVEMENT OF THE SOIL	10	17	15.5	27	8.5	30	28	7.5	8	8.5	13	13
EXCESSIVE SURFACE ACCIDENTAL LOADS	17.5	21	21	23.5	17.5	23	22	11.5	10.5	13	16	15.5
LOW TEMPERATURES	7.5	14	9	19	8	20	19	7.5	9.5	7.5	9.5	11
WATER HAMMER	15	24	14.5	24.5	17	23	22	11.5	13.5	12	14	16
ROAD WORKS	22.5	32	27	36	23.5	43	40	16.5	17	19	23.5	24

Source: Adapted from Moruzzi (1987)

As can be seen from Figure 4.6, metallic pipes provide better resistance than non-metallic pipes. Steel pipe with welded joints provides the best overall resistance, though this is not the most common material used in Canada. Of the more common materials, ductile iron with flanged joints is the strongest metallic pipe. Asbestos cement followed by welded P.E. provide the greatest resistance of the non-metallic pipes. It is important to note that the use of lower resistance materials such as asbestos cement and the more recent use of P.V.C. has been widespread since the 1950s. It has also become obvious in some municipalities that these newer materials do not always provide service lives which match those of the more traditional iron pipes.

In Canada, the majority of pipes in need of rehabilitation are either cast iron or asbestos cement which respectively make up 85 percent and 9 percent of the pipe in the ground over 30 years old (MU 1961), with the remaining 6 percent being either steel, wood, or a variety of less used materials.

In A.C. pipe, water which has a depressed pH or is overly soft and therefore lacking calcium can leach the calcium components out of the cement thus releasing asbestos fibres (AWWA 1974, Davis et al 1979, Commins 1979, Toft and Marks 1983, Nebesar and Riley 1984). Thus, some utilities are having to replace A.C. lines after only twenty years of service (Robinson 1991, Maclean 1991).

Still, when interpreting the results of Figures 4.5 and 4.6, some caution should be exercised. In some applications, lower resistance does not necessarily mean poorer performance. For instance, in the case of slip on type pressure and sleeve type joints with rubber ring gaskets, the lack of resistance to axial loads can be an asset, providing a non-rigid discontinuity which can move to reduce axial stresses due to thermal expansion or contraction.

Figure 4.6: Degree of resistance to leakage sources

REASONS FOR LEAKAGE IN PIPES / JOINTS INDEPENDENT OF ANY TYPES OF STRESS	TYPE OF SURFACE OR COATING (Int. and/or ext.)						TYPE OF PIPE MATERIAL						TYPE OF JOINT					SERVICE PIPE TYPE		
	BIT	PLA	AC	ST	CI	DI	CI	DI	ST	PVC	PE	FRP	W	F	P	SL	SQ	ST	Cu	PLA
EXTERNAL CORROSION	6	10	10	3	4	5	4	5	3	10	10	10	7	8	9	8	10	6	7	9
INTERNAL CORROSION	4	10	9	1	2	3	2	3	1	10	10	10	3	9	9	8	10	2	7	8
AGEING OF MATERIALS	3	6	10	10	9	10	9	10	10	6	5	?	10	9	7	6	6	10	6	9
LEAKAGE OF JOINTS	-	-	-	-	-	-	-	-	-	-	-	-	10	9	7	6	9	-	-	-
TOTAL	13	26	29	14	15	18	15	18	14	26	25	20+	30	35	32	28	35	18	20	26
LEGEND	BIT: bituminous PLA: plastic AC: cement or asbestos cement ST: steel CI: grey cast iron DI: ductile iron						CI: grey cast iron DI: ductile iron ST: steel PE: polyethylene PVC: polyvinyl chloride FRP: fibre reinforced plastic						W: welded F: flanged P: pressure SL: sleeve SQ: squeezed					ST: steel Cu: copper PLA: plastic		

Source: Adapted from Moruzzi (1987)

In addition, because of the relatively young age of the plastics used in water distribution there is little data on the long term deterioration of these products.

4.3. Age as an Indicator of Pipe Condition

A number of authors have suggested that age is not a good indicator of the specific condition of a water main (Arnold 1960, O'Day 1984, AWWA 1986a). Arnold (1960) notes that many 100 year old pipes still operate effectively, while 50 to 75 year old pipes require intensive maintenance. The AWWA (1986a) found poor correlation between pipe age and anticipated leak/break rates. However, both O'Day (1984) and McIntyre and Elstad (1987) concede that while age cannot be used to predict individual break rates, it can be used to roughly indicate average break rates by age group and thus the general condition of longer aggregate samples.

While age may not be the best indicator of system condition, in many systems where maintenance and repair information are lacking, it is often the only indicator available. For this reason, it remains a basis for preliminary national or regional condition assessments.

4.3.1. Historical Development of Piped Systems

The transmission of water through pipes is an old technology. In 180 B.C. the Phoenician Hellenistic Pergamon constructed a piped system that brought water from a nearby mountain under a pressure of 16 to 20 atmospheres (de Camp 1990). Three hundred years later, the Romans developed the famous aqueducts which carried distant waters to feed into systems consisting mostly of lead pipes. Lead was used extensively for pipes as wood tended to split and rot; tile and concrete, though durable, were poor in tension and thus could not withstand the internal pressures; and bronze, while strong, was hard to work and expensive (de Camp 1990). The ill effects of using lead pipes to carry water, though suspected in the Roman times, were not positively proven until Benjamin Franklin diagnosed lead poisoning in 1768 (de Camp 1990).

The Roman systems suffered from many of the same problems faced by today's systems (leakage, cracking, etc.) and required a great deal of maintenance. Even after massive repairs through the centuries, the systems along with the Empire had all failed by 1000 AD. In Paris, the Roman aqueducts destroyed by Norse invaders in 900 AD were replaced by marginal aqueducts around 1200 AD, but it was not until 1600 AD, after many disputes over scarce piped water, that Henry IV decreed that users must pay fees large enough to support the water system. Eventually a pumping system was built to raise the river water and carry it to his palace, with the excess water being turned over to the public. This marked the beginnings of Paris' modern system (de Camp 1990).

Over time, water systems became more elaborate and wide-spread. Early systems in England utilized wooden "tree trunk" mains with the use of iron pipes as the material of choice emerging in the early 1800s. Between 1812 and 1819 some 600 kilometers of wooden "tree trunk" mains were replaced by vertically cast iron mains in London, England, many of which are still in use today (Edwards and Cox 1982).

In North America, wood pipes were often installed because of the expense of cast iron pipes, though the wooden pipes in many of these early systems would frequently leak or burst. Wood pipes were often used in areas where water supplies were plentiful and therefore system reliability less important, such as in British Columbia and Quebec, and were typically installed with the idea that once revenues were sufficient, they would be replaced by cast iron pipes (Anderson 1988).

The large scale use of wood never really developed. In 1961 only 48 communities in Canada had wood stave pipes still in their systems, with 24 in British Columbia and 12 in Quebec, representing only a small fraction of the 1,878 systems which were in Canada at the time.

4.3.2. Development of Modern Pipe Materials, Construction and Design Techniques

While the exact age of a pipe may not be an accurate indicator of its condition, the year or period it was installed still holds valuable clues to its condition. Over the years, new materials and construction techniques have emerged which have improved some characteristics of the pipe, while degrading others.

Today the majority of the pipes in the ground are iron, either in the form of cast iron or the newer class of ductile iron developed in the 1960s. The relative high cost and heavy weight of iron pipes stimulated the development of other materials for pipe such as asbestos cement (A.C.) which was first introduced in North America by Johns-Manville Corporation (U.S.A.) in 1929 and became popular in the late 1950s (Nebesar and Riley 1984). It had the advantages of being light weight, low cost and resistant to external corrosion since it did not carry electrical current. Eventually, concern over asbestos fibres and the development of plastics such as Polyvinyl Chloride (P.V.C.) and Polyethylene (P.E.) lead to the demise of A.C. pipe. P.V.C. and ductile iron remain the predominant material types installed in distribution systems today.

A better understanding of construction techniques has benefitted through continued experience and research with piped systems. As an example, the importance of continuous, tamped, select bedding material under a pipe was not totally understood until the 1930s and 1940s. Many of the early mains were often laid in corrosive backfill and the AWWA's 1927 "Handbook of Cast Iron Pipe" actually recommended blocking under the bells, a situation which can cause excessive beam stress since the main is not continuously supported (AWWA 1986a).

Significant advances have also been made in joint design with the introduction in the 1930s of the mechanical and roll-on joint to replace the older lead-caulked bell and spigot and the introduction of the push-on type rubber joint in the 1940s which increased the seal and pipeline flexibility to reduce leakage (AWWA 1986a).

Design techniques have also improved. For iron mains laid between 1908 and 1939, wall thickness was based only upon anticipated internal working pressures and bedding conditions, while after 1939 external loads were also taken into account. Modern iron pipe design practises are now based upon theoretical principles such as the application of a factor of safety of 2.5 applied to two separate load conditions: the first with earth external loads and both working and surge internal pressures, and the second with earth and truck external loads and only working internal pressure. The greater wall thickness from these two loadings is chosen.

While the development of new materials and the understanding of loading and corrosion mechanisms have improved vastly since the turn of the century, improvements in technology have not always resulted in improved pipe performance and longevity. The refinement of modern design principles have meant that some factors of safety have actually been reduced over the 1908 standards, which were quite conservative due to the greater uncertainties of design. The 6" (150 mm) diameter pit cast iron pipe of 1908 by today's standards would actually provide a factor of safety of 7.3 over working and surge pressures, and 14.8 over the external earth and truck loads (AWWA 1986a).

Other advances, which resulted in greater reliability and reduced material and installation costs, also reduced overall durability. For instance, the introduction of ductile iron in the 1960s meant the bursting tensile strength, rupture strength, and tensile strength measures were increased by a factor of three over the pit cast pipes used from 1850 to the 1930s, and by a factor of two over the centrifugally cast pipes used from the 1930s to the 1960s. This increase in material strength allowed pipe wall thicknesses to be reduced by 25 percent over the 1908 pit cast main standards. While resulting in considerable construction cost savings, the reduced wall thickness meant that the pipes were more vulnerable to the effects of corrosion, which is highly dependent on wall thickness. A study has confirmed that pipes installed since the 1950s have performed relatively poorly compared to earlier installed pipes (Andreou and Marks 1987).

4.3.3. Modern Pipe Design: Rigid and Flexible Pipe

There are two basic classifications of modern pipe designs: rigid and flexible. Rigid pipe is characterized by a high resistance to crushing loads, but is brittle and cracks under very small deformation of the vertical diameter, while flexible pipes, in the absence of side supports, will deform progressively without cracking under a slowly increasing crushing load (Clarke 1968). Flexible pipes can deflect up to 2 percent without structural distress (Moser 1990, p. 4), and through this can transfer part of the vertical soil and traffic loads into a radial thrust, thereby activating the passive earth pressures on the side of the pipe which produce an arcing effect to help support the loads (Moser 1990 p. 21). A rigid pipe, on the other hand, can not produce such an effect and therefore must be designed with sufficient resistance to carry the entire vertical load itself. Rigid pipes common to water distribution systems include cast iron, asbestos cement, reinforced concrete, composite steel and concrete, while flexible pipes include steel, ductile iron, and most plastics.

The different characteristics of rigid and flexible pipes mean different design procedures are followed for each. In general, the construction techniques used for modern flexible pipes are much more dependent on proper installation versus the older rigid pipe installations which relied more on the strength of the pipe rather than the proper bedding and compaction requirements of modern flexible pipes. Because of space limitations, the modern design methodology for rigid and flexible pipe will not be described in detail, but a number of excellent references which describe the current design practises are available (Clarke 1968, Young and Trott 1984, Stephenson 1989, Moser 1990).

4.4. Other Factors Influencing Pipe Performance

Material properties, joint types, and age are not the only characteristics of a pipe which influence its structural performance. Geometry, seasonal variations, water attributes, and system operation are also important factors influencing a pipe's lifecycle.

The geometry of a pipe is measured in terms of its wall thickness and diameter. Bending due to overburden or loss of bedding is especially critical in small diameter pipes which are susceptible to circumferential cracking due to the relatively small moments of inertia compared to larger diameter pipes (AWWA 1986a). Larger diameter pipes, in general, are more resistant to external forces than the small diameters, but are susceptible to longitudinal cracking from crushing loads due to heavy vehicles and frost effects. (O'Day 1983). A number of sources have shown that breakage rates are highest among the small diameter pipes. In Philadephia and Denver, annual repair rates per mile for pipes 6" (150 mm) in diameter or smaller are typically 2 to 5 times greater than for larger pipes up to 16" (400 mm) in diameter and 7 to 25 times greater than for the largest pipes over 16" (400 mm) in diameter (AWWA 1986a).

Break rates also tend to be seasonal in nature, being highest in the cold winter months especially in cities which experience extreme summer and winter temperature variations. Within Canada, this includes nearly all communities, with the exception of those in the more moderate coastal zones, such as Vancouver and Victoria. In Calgary for instance, between 1975 and 1980 the monthly failure rate during the cold months (November to March) was approximately five times the failure rate which occurred in the summer months (June to September)(Caproco 1985). In the northern sections of the U.S., between 60 and 70 percent of the annual main breaks occur in the four winter months of November to February (O'Day 1983).

The lower temperatures in the winter increase the tensile stress on mains due to temperature induced contraction, and can increase the external stresses caused by soil-moisture expansion from frost penetration (O'Day 1983). Flexible joints reduce the effects of temperature induced stress due to contraction, but the presence of valves, services, and structures can effectively restrict movement and increase the stress. Soil-moisture expansion is a significant factor especially in areas where the bedding has been disturbed or pipes have been weakened by corrosion.

The spatial distribution of breaks is also an important characteristic of piped systems. Kettler and Goulter (1985) found that pipe breaks in Winnipeg actually occur in clusters, with 22 percent of all breaks occurring within one meter of a previous failure, and 46 percent of the failures occurring within 20 metres of a previous failure. Clark et al (1982) also notes that in two utilities observed, a small percentage of the pipes have the most problems; after 40 years, over 52 percent of the pipes had no maintenance events. This implies that massive system replacement may not be the best solution; rather programs aimed at the replacement of troublesome sections may be more effective.

Apart from the characteristics of the individual pipes, factors related to the overall system environment also contribute to increased maintenance costs. Clark et al (1982) found utilities with soft water (< 60 mg/L as $CaCO_3$) to have 31 percent higher total unit costs than those with hard water. In addition, higher leakage rates were found in systems with relatively few pressure zones (such as those served on flat terrain by a groundwater source) probably due to the greater system wide impact of pressure variances.

4.5. Corrosion Processes

Corrosion is a primary cause of a water main deterioration. Corrosion typically refers to process in iron based pipes such as steel or cast-iron or ductile iron where an electrochemical reaction between the pipe metal and its adjacent environment causes the pipe to lose its ferrous constituents. But corrosive environments can also attack cement based pipes, such as concrete and asbestos cement, where the leaching out of the lime component of the cement produces a softening of the pipe wall.

The corrosion process is a complex phenomena which can not be eliminated but can be controlled. It may be uniform along a pipe or localized in nature, attacking only a small area of a pipe. A number of excellent references are available which deal with the corrosion of water pipes (Parker and Peattie 1984, AWWA 1989, Smith 1989).

There are three major types of corrosion associated with iron based water mains:

1) internal
2) external
3) electrolysis from stray d.c. current

4.5.1. Internal Corrosion

Internal corrosion is predominantly a problem in older unlined cast iron and steel pipes. It is initiated at a discontinuity such as a scratch or rust where there is an electrical potential difference along the pipe wall. Water acts as an electrolyte, accepting iron ions from the anode while electrons flow from the anode through the pipe wall to the cathodic area where hydrogen ions are combined to form free hydrogen gas or react with oxygen to form hydroxide ions. At the anode, ferrous ions react with water to form ferrous hydroxide, which is moderately soluble, or, if the water contains high concentrations of dissolved oxygen, ferric hydroxide which is highly insoluble. If ferric hydroxide can precipitate at the surface in large enough quantities, a tubercule will form, and in doing so will accelerate the corrosion process and cause pitting in the adjacent anodic area. A number of factors related to the characteristics of the water which either enhance the corrosion process, or inhibit it are presented in Table 4.3.

Inhibitors generally allow the formation of a protective layer on the corrosion site, while the corrosion enhancers limit the formation of this layer and accelerate the process. The growth of microorganisms which feed on the nutrients in the water and off the corrosion products can pose a health concern. There are two common methods for assessing corrosion potential: coupon tests and corrosion indices. Coupon tests involve the periodic taking and weighing of a sample of the pipe wall.

Table 4.3: Water characteristics related to internal corrosion

Factors Which Can Enhance Corrosion:	Factors Which Can Inhibit Corrosion:
Low pH (< 7.5)	High Buffering Capacity
High Dissolved Oxygen (> 0.3 mg/l)	High Silica
High Total Dissolved Solids (> 500 mg/l)	High Calcium
High Temperatures (> 60 degrees F.)	High Phosphates
High Flow Rates (> 4 ft/sec)	Hard Water (>150 mg/l as $CaCo^3$)
Stagnation (< 0.5 ft/sec)	
Low Alkalinity (< 30 mg/l as $CaCO_3$)	
Chlorine (> 200 mg/l)	
High Sulfates (> 300 mg/l)	
Hydrogen Sulfide (> 0.1 mg/l)	
Growth of Microorganisms (on pipe wall)	
Soft Water (<75 mg/l as CaCO3)	
High Soluble Iron	

Source: Adapted from AWWA (1986a); Critical values from Ryder (1989) and AWWA (1989).

While this is the most direct means of assessing the condition, it is quite costly and time consuming and is therefore often practised by only the largest utilities with serious corrosion concerns. The predominant corrosion indices are based on the distribution water's tendency to precipitate calcium carbonate and therefore resist changes in pH. Levels of hardness, alkalinity, corrosive ions (chlorides and sulfates), and a variety of other water quality parameters are included in such indexes. The AWWA (1989) outlines many of the indices which have been developed, but the most common remains the Langelier Saturation Index, or LSI. The Langelier Saturation Index, or simply Langelier Index (LI) is essentially a comparison of the observed pH with the calculated pH at calcium carbonate saturation. While it provides an indication that a water is corrosive, it does not indicate the degree of corrosiveness (AWWA 1989, Hunsinger et al 1989). A negative LI index indicates a potential for corrosiveness, while a positive LI indicates the potential for deposition of a scale. The Langelier Index is calculated as follows:

$$LI = pH - pH_s \tag{4.1}$$

where: LI = Langelier Index
pH = observed pH of water
pH_s = pH at calcium carbonate saturation

and,

$$pH_s = T + B - \log (Ca^{2+}) - \log (A)$$

where: T = constant (function of water temperature)
B = constant (function of total dissolved residue)
A = total alkalinity (as mg/L of $CaCO_3$)

The LI index has its limitations in that it does not predict the optimum amount of calcium carbonate required to provide an effective protective layer without forming an excessive layer of precipitation which reduces pipe capacity. Water of pH 6.5 to 9.5 with a positive LI is generally not corrosive, but may be under certain conditions given the presence of other corrosion enhancers in the water (AWWA 1986a).

A modified LI has been developed specifically for asbestos cement pipe which is known as the Aggressiveness Index, or AI. The Aggressiveness Index is based on the pH, hardness, and alkalinity of a water supply. An AI less than 10 indicates water which is aggressive, 10 to 12 indicates moderately aggressive, and over 12 indicates non-aggressive. AI is calculated as follows:

$$AI = pH + \log (A*H) \tag{4.2}$$

where: AI = Aggressiveness Index
pH = observed pH of water
A = total alkalinity as mg of $CaCO_3$
H = calcium hardness as mg of $CaCO_3$

Buelow et al (1980) in a study of 10 distribution systems in the U.S. concluded that water is not expected to attack AC pipe when the AI is greater than 11, and that high concentrations of some metals, such as iron, in the water may inhibit corrosion through the formation of a protective layer even if the AI is lower than 11.

Water with a low AI, due to a depressed pH or low alkalinity or hardness, will leach the calcium components out of the cement thus releasing asbestos fibres (Davis et al 1979, Toft et al 1981 as cited in Hunsinger et al 1989). Generally soft waters are those with hardness of 0 to 75 mg/l as calcium carbonate, while moderate waters have 75 to 150 mg/l, and hard waters have 150 to 300 mg/l (AWWA 1989).

Once problem with corrosion has been identified, various methods of control can be considered. Three general techniques are common:

1) the use of non-metallic pipe materials or protected metallic pipe,
2) the cleaning and cement lining of the main,
3) the introduction of corrosion inhibitors to the distribution water.

Replacement of corroding pipes with plastic or lined ductile iron pipes is now quite common. When significant life is left in a metal pipe, it can be economically renovated using cleaning and cement lining techniques which can last up to 20 to 30 years even in an aggressive environment. Inhibitors are typically added at the treatment plant and can include phosphates and silicates which pacify the corrosion reaction, or lime, limestone, caustic soda, soda ash, and sodium bicarbonate which raise the pH (Hunsinger et al 1989).

In Canada, internal corrosion is a significant factor in cities like Vancouver where it accelerates the corrosion of copper and iron pipes (Millette and Mavinic 1987) and in Winnipeg, Burnaby, and North Vancouver where it is attacking asbestos cement pipes

(Hickman 1984, Robinson 1991, Maclean 1991). In the greater Vancouver area, the water is extremely soft and aggressive, with an LI of -5.1 and an AI of 7.0 (Bratton et al 1986) and multi-million dollar plans for the addition of inhibitors are now under way (Mavinic 1990).

Failing to deal with internal corrosion effectively can result in health concerns due to excessive concentrations of corrosion products and metal ions, aesthetic concerns related to staining of fixtures and discoloration of the water, and economic effects in the form of repair and premature replacement of deteriorated pipes. The AWWA (1989) outlines an eleven step process to evaluate corrosion which includes reviewing water quality data, potential effectiveness of treatment processes, and costs and benefits realized by both the utility and the consumers.

4.5.2. External Corrosion

The electrochemical process involved in external galvanic corrosion, otherwise known as "graphitization" is similar to that of internal corrosion. A galvanic cell is produced when the metal pipe is in contact with corrosive soils of low resistivity. Iron ions go into solution at the anodic area to form rust scales on the pipe, leaving only a weak carbon skeleton. At the cathodic area hydrogen ions or oxygen ions are formed. The build-up of rust at the anode or hydrogen ions at the cathode can inhibit the corrosion process, but the presence of dissolved oxygen in the soil can again accelerate the process as dissolved oxygen reacts with the hydrogen ions at the cathode to form water. Pitting of the pipe will then occur at the relatively concentrated anodic reaction site, which is often only 5 percent of the area of the cathodic site (AWWA 1986a). The connection of dissimilar metals, such as copper pipe and brass service fittings attached to iron mains, can increase the potential for a galvanic reaction. Although iron is anodic to brass and copper, two factors make this situation less than critical. First the iron pipes are usually much larger than the smaller copper service pipe, thus there is a large anode with a small cathode which is the weakest of the bi-metallic corrosion cells (Smith 1989). Secondly, soil resistivity may be sufficient to suppress current flow and subsequently the action of the corrosion cell.

Soil resistivity is an important factor in assessing of the corrosive potential of a pipe's environment. Soil resistivity is a measure of the average electrical resistance of the soil and decreases with high moisture contents and heterogeneity of the soil. Morris (1967) notes a resistivity of 1500 ohm-cm or less indicates the presence of soluble salts sufficient for an effective electrolyte.

Soil resistivity combined with soil to pipe potential are the main predictors of actual pipe corrosion (Smith 1989). The corrosion process is generally inhibited by high soil resistivities and accelerated by high soil to pipe potentials. Soil to pipe potential is the voltage potential between the pipe and its adjacent soil; when this potential is high and the soil resistivity is low, a corroding area is often identified. This is the most common of the electrolysis testing techniques, though others are outlined by Smith (1989).

The corrosion potential associated with soil resistivity varies among pipe materials. Soil resistivities above 2,000 ohm-cm are generally not corrosive to cast iron, while for steel pipes, resistivities up to 2,000 ohm-cm are extremely corrosive, between 2,000 ohm-cm to 6,000 ohm-cm they are moderately corrosive, and above 6000 ohm-cm they are non-corrosive (Smith 1989).

As in Table 4.4, soil resistivity, pH, redox potential, sulfide content, and moisture content are important indicators of the need for corrosion protection on cast iron pipes.

Table 4.4: Soil corrosion evaluation rating for cast iron pipes

		Points
Resistivity	< 700	10
	700-1000	8
	1000-1200	5
	1200-1500	2
	1500-2000	1
	> 2000	0
pH	0-2	5
	2-4	3
	4-6.5	0
	6.5-7.5	0 *
	7.5-8.5	0
	> 8.5	3
Oxygen Reduction Potential	> 100 mv	0
	50-100 mv	3.5
	0-50 mv	4
	negative	5
Sulfides	positive	3.5
	trace	2
	negative	0
Moisture	poor drainage, always wet	2
	fair drainage, generally moist	1
	good drainage, generally dry	0

* - if sulfides are present and low or negative redox results are obtained 3 points shall be given for this range.

Note: a total of 10 points indicates a soil corrosive to cast iron pipe and protection is indicated.

Source: Smith (1989)

Calgary has one of the best documented corrosion problems in Canada. Soil resistivities have been extensively measured at thousands of locations in the city, with resistivities of 1,000 ohm-cm to 2,000 ohm-cm common (Caproco 1985). The corrosive soils resulted in annual breakage rates in the mostly cast and ductile iron system of nearly 50 breaks per 100 kilometres in 1979 at nearly twice the national average. After extensive study and the implementation of an extensive corrosion control program and main replacement program since 1982, the rate is now down to about 20 breaks per 100 kilometres per year (James and Nq 1991).

A number of processes may increase external corrosion rates. Leaking pipes or abandoned services can both increase the soil moisture and flush away corrosion products from the pipe surface (AWWA 1986a). Soil resistivities may also be depressed by infiltration of road salts in snow melt or high tidal intrusions.

4.5.3. Stray Current Corrosion

The final type of corrosion in due to the presence of stray direct electrical current. The process involves the conduction of external current from a power source such as an electrical trolley with ground rails, through the soil and through the pipe. Where the current discharges from the main, anodic corrosion will occurs.

The methods of controlling external corrosion are generally directed at new mains with considerable life remaining since there is often little economy in the protection of old mains (AWWA 1986a). The techniques include: electrolysis control, polyethylene wraps, and plastic and epoxy coatings. Electrolysis control includes both galvanic and impressed current cathodic protection. Galvanic cathodic protection refers to the connection of a sacrificial anode made of zinc or aluminum which corrodes, thus making the entire pipe the cathode. Impressed current protection induces reversed the cathodic reaction and is used especially when significant stray current is present but has a draw back of requiring a constant power source. Polyethylene wrap is a good control, but makes repairs difficult. Plastic and epoxy coatings are also good, but care must be taken not to chip them and provide a site for a concentrated anodic reaction.

4.5. Deterioration Criteria

The previous sections outlined a number of factors which make simple cause/effect relationships both difficult to understand and often impossible to apply when assessing the deterioration of water distribution systems. The complexity of the deterioration process has resulted in the development of empirical and statistical techniques to predict the deterioration, though they often receive only limited application by utilities. Often pipe deterioration assessments and the resulting rehabilitation or replacement programs are based on "seat-of-the-pants" techniques or generalizations related to age or type of pipe, an approach that has been rejected by many authors as being inefficient (O'Day 1983, Andreaou and Marks 1987).

Four major criteria are recommended by AWWA (1986a) to best evaluate the condition of a water main:

1) structural integrity,

2) leakage,

3) hydraulic conditions, and

4) water quality.

Since buried water mains are inaccessible, measures for the above criteria have been developed using indirect indicators. These indicators are listed in Table 4.5.

The degree to which municipal water utilities have formally adopted these criteria into a pipe replacement and rehabilitation program varies widely across North America, depending largely on the utility size, the available resources, the severity of the problem, and the individual philosophy of each manager. In general though, the application of formal programs is lacking. Mays (1989) finds that in a survey of the methods used by utilities in the U.S., the application of computerized information and data base systems related to water distribution systems is almost non-existent. While many of the surveyed municipalities have hydraulic simulation capabilities, none have the networks stored in an accessible data base. In addition, none of the municipalities utilize methodologies for the optimal upgrading of aging water mains and when new systems develop, simple trial and error procedures aimed at minimum cost designs are still the most common.

Table 4.5: Criteria used to evaluate water main deterioration

CRITERIA	METHOD	INDICATOR	POTENTIAL CONSEQUENCES
Structural Integrity	break record analysis	high break rate	- high repair costs - emergency service disruption - consumer service disruption - water contamination (from exposure)
Leakage	leak survey	high water loss	- excessive water demand - high pumping and treatment costs - pipe bedding wash-out - increased moisture in corrosive soils - water contamination (from backflow)
Hydraulic Conditions	flow tests and models	low pressure and inadequate flows	- inadequate fire flows - service level complaints - corrosion and tuberculation indicated - undersized mains indicated
Water Quality	lab tests on water	high concentrations of substances	- poor taste and odor characteristics - fixture stains from corrosion products - bacterial contamination in pipes - poor installation indicated - inadequate treatment indicated

Ideally, all four criteria are to be monitored and eventually input into the rehabilitation decision process. However, current applications tend to focus on the hydraulic conditions and structural integrity, both of which are easy to monitor and are characterized by easily identifiable costs. As such, most utilities base pipe replacement programs on high maintenance costs or inadequate flows and pressures.

While water quality is monitored on a regular basis, it is sometimes difficult to distinguish between problems originating at the source and those originating in the pipes. Typically, efforts at solving water quality problems focus on the treatment plant rather than the distribution system. Still, serious public health concern over water quality, if resulting from the distribution system, can be a powerful determinant in the decision regarding when a pipe should be replaced, although its occurrence is probably the least frequent.

When a rehabilitation program is in place, often the least amount of attention is paid to leakage criteria as leaks are difficult to detect and the nature of the problem can be such that many small leaks may be spread over a large area of the system, making implementation of a program quite costly. Specific locations where leakage is a problem can only be determined by sonic or other leak detection tests, while pressure and flow problems can be easily pinpointed through customer complaints or simple flow tests. Water quality problems can also be identified through customer complaints and through frequent water quality tests by health authorities. Pipe sections with high repair rates are typically identified through the utility's maintenance records.

CHAPTER 5: CONDITION ASSESSMENT AND MITIGATIVE TECHNIQUES

5.0. System Condition Assessment

There is no accepted standard procedure yet developed which can be used to assess the condition of a water distribution system and then determine the appropriate course of mitigation. From the literature, effective rehabilitation programs typically include five major components:

1) development of a detailed database and inventory of piping system elements,
2) a detailed condition assessment (including survey-inspection for leakage and flow testing, and break analysis) using descriptive, predictive, and physical models
3) "needs study" to analyze deficiencies and set priorities,
4) systematic maintenance, repair, and renovation program,
5) systematic construction program to replace pipe beyond feasible repair or renovation.

5.1. System Inventory

Before a utility can even begin to assess the existing condition and future needs of a system, a detailed inventory of the system must be developed. The development of graphical information systems (GIS), digital mapping, computer aided drafting (CAD), database systems and spreadsheets for personal computers has advanced rapidly and costs have come down over the past ten years to a point where even the smallest communities can have access to sophisticated technologies.

Rodi (1987) notes that up that to 90 percent of a municipality's information has some type of geographical reference. MacLaren (1983) suggests that when setting up such system, references should be converted to standard provincial mapping record systems and a block plan of each element should include the information outlined in

Table 5.1.

Table 5.1: Inventory information for water distribution systems

- identification code for each element
- the element type (pipe length, valve, meter, hydrant, service, manhole)
- the element class (trunk, arterial, local, private)
- location according to reference system
- pipe size and length
- material type
- lining or coating
- date of installation
- burst or leak record and location
- repair record (leak, repair, relining)
- complaint reports (flooding, low pressure)
- initial cost or replacement costs
- cost of repairs by year
- maintenance and service records (flow tests, hydrant flushing, valve rotation, etc.)
- condition rating

Source: MacLaren (1983)

While there are programs available which incorporate such information, the use and understanding of them needs to be better promoted. The sheer volume of individual software packages now available has made it difficult for small communities to decide on the best system to meet their needs. The Government of Ontario has recently developed a computerized inventory program, WIMS, for water distribution systems which can be used as an effective basis for implementing an ongoing maintenance and rehabilitation program (Phillips et al 1991).

5.2. Condition Assessment Techniques

The following section will outline the two basic analytical techniques which have been identified and developed by a variety of agencies to assist in making optimal rehabilitation decisions. The two techniques include the more basic descriptive techniques and the more sophisticated predictive techniques.

5.2.1. Descriptive Analysis

A descriptive analysis is the most basic and analytically simple method of determining baseline information regarding the condition of a water system. The most common descriptive analysis involves the simple cross tabulation of deterioration criteria, such as leaks or breaks, with pipe characteristics such as diameter, location, soil type, operating pressure, or traffic counts on the road above. This analysis can determine basic areas where future rehabilitation effort should be concentrated. A tabulation of breakage trends versus physical location or soil type may be useful in determining "hot spots". To assist in determining the performance of newer pipes versus old, a comparison of breakage rates among different pipe installation periods or material types may be useful. Factors which are common to such tabulations are given in Table 5.2.

Table 5.2: Descriptive analysis factors

Dependent Variables	Independent Variables
Main Breaks	Soil Type
Leaks	Soil Resistivity
Emergency Repairs	Heavy Truck Volumes
Pressure Loss	Average Bury Depth
Maintenance Costs	Time (Day, Month, Year)
Damage Claims	Pipe Material
Customer Complaints	Installation Period
Failed Quality Tests	Intensity of Development
	Operating Pressure (Absolute)
	Pressure Differential
	Pipe Diameter
	Past Renovation Carried Out
	Freeze/Thaw Cycles Since Installed

This type of analysis is only as good as the type and format of information available. For instance, a utility may itself record emergency repairs, but may have to transfer the data to a useable form such as a spreadsheet or database. Other data such as soil types, traffic volumes, or intensity of development may have to be acquired from other departments or agencies such as municipal traffic engineering departments, provincial lands departments, or Statistics Canada. Specialized data, such as soil resistivities, must be specially gathered by the utility once the need for such data is justified.

Historical records are also invaluable. In New York City, for instance, old maps of original stream beds which existed before the City developed are kept on hand as leaks and breaks can often surface blocks from the actual source, having travelled along the old stream routings. Such maps can also give important insights into soil conditions which can develop into specific corrosion areas.

The method of analysis can also vary. It can be as simple as placing colored pins on a system map or it can incorporate widely available spreadsheet programs which allow graphing of both bar type and linear plots, and which can accommodate more sophisticated techniques involving statistical distribution and multiple regression. Regardless of the method, the analysis is still only as good as the data available.

5.2.2. Predictive Analysis

In the past decade, a number of studies have been conducted which attempt to model the breakage mechanism of a water main (Shamir and Howard 1979, Clark et al 1982, Andreaou and Marks 1987). Shamir and Howard (1979) found that breakage trends in the City of Calgary seemed to increase exponentially once an initial break had occurred. Based on this observation, an expression for the prediction of future breakage was formulated:

$$N(t) = N(t_o)e^{A(t-t_o)} \tag{5.1}$$

where,
- t = time in years,
- t_o = base year for the analysis,
- $N(t_o)$ = number of breaks per 1,000 foot length of pipe in the base year,
- $N(t)$ = number of breaks per 1,000 foot length of pipe in any given year "t",
- A = break growth rate coefficient (per year).

In this study, growth rate coefficients were found to range between 0.05 and 0.15, while the number of breaks in the base year ranged from 0.10 and 0.25 breaks per 1000 feet per year, which is equivalent to between 33 and 82 breaks per 100 kilometres per year. To calculate the expected number of breaks over a given time period, equation 5.1 is integrated with respect to time.

Clark et al (1982) uses a multiple regression technique to predict both time to first repair and subsequent repair trends, with a repair being due to either leaks or breaks. Repair data for the study was provided by a large utility (11.39 m^3/day). From the regression analysis, the time to the first repair was estimated by:

$$NY = 4.13 + 0.338D - 0.022P - 0.265I - 0.0983RES - 0.0003LH + 13.28T \tag{5.2}$$

$$R^2 = 0.23$$

where,
- NY = number of years to first repair,
- D = diameter of pipe, in inches,
- P = absolute pressure with a pipe, in p.s.i.,
- I = percent of pipe overlain by industrial development in a census tract,
- RES = percent of pipe overlain by residential development in a census tract,
- LH = length of pipe in highly corrosive soil, in feet,
- T = pipe type (1 = metallic; 0 = reinforced concrete)

While such an equation is quite system specific and should not be used in the prediction of trends in other systems, it can still be seen that generally the larger the pipe diameter and the lower the operating pressure, development intensity, and presence of corrosive soils, the longer a pipe will function without the need for repair.

In order to predict the number of expected repairs, Clark et al (1982) carried out another regression analysis with the resulting equation:

$$REP = (0.1721)(e^{0.7197})^{T}(e^{0.0044})^{PRD}(e^{0.0865})^{A}(e^{0.0121})^{DEV}(SL^{0.014})(SH^{0.069}) \quad (5.3)$$

where,

REP	=	number of repairs,
T	=	pipe type (1 = metallic; 0 = reinforced concrete),
PRD	=	pressure differential, in p.s.i.,
A	=	age of pipe since first break, in years,
DEV	=	percent of land over pipe in low and moderately corrosive soil,
SL	=	surface area of pipe in low corrosive soil, in sq. ft.
SH	=	surface area of pipe in highly corrosive soil, in sq. ft..

The above regression equations can be substituted into equation 5.1 as NY in equation 5.2 is equivalent to t_o (the base year) in equation 5.1, and the constant (0.0865) in the fourth term of equation 5.3 is equivalent to A (the growth rate in equation 4.8).

Andreaou and Marks (1987) present another method of predicting the break failure patterns based on proportional hazards and Poisson-type models. This method is a further refinement in that it recognizes various stages in a pipe's life, rather than assuming that after an initial break, a pipe will invariably break at an exponentially increasing rate.

The basic approach considered by Andreaou and Marks (1987) is based on the premise that the operation life of a piped system, like many other multi-component engineering systems, can be represented by a bath-tub shaped baseline hazard function (see Figure 5.1). Such functions are characterized by three phases: a start-up phase, a normal operation phase, and a wear-out phase (Bury 1975). Applied to a piped system, the start-up phase is generally the one or two year period of initially high repairs which diminish as the initial "bugs" are taken out of the system. During this period, the contractor responsible for the installation of the pipe is typically responsible for the repairs.

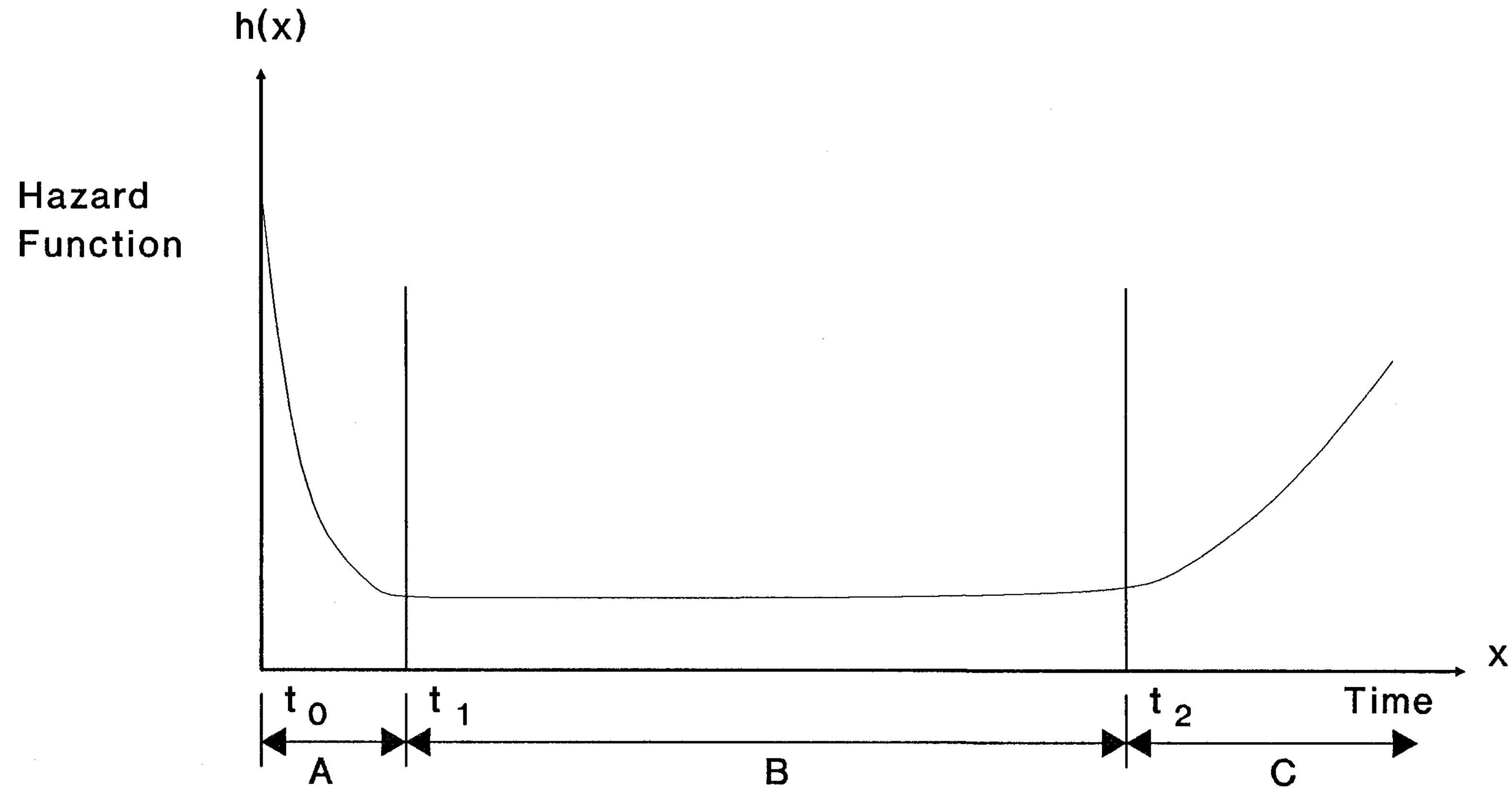
Once this initial period has passed, the normal operation phase is entered into. Andreaou and Marks (1987) refer to this as the slow breaking state, with pipes having experienced few (usually no more than two) and infrequent breaks. The probability of failure can best be described by a proportional hazards type model, similar to equation 5.1 with the form:

$$h(t) = h_o(t)e^{bz} \tag{5.4}$$

where,
- $h(t)$ = hazard rate (breaks per year) at time t,
- $h_o(t)$ = baseline hazard function, estimated from a regression analysis,
- z = vector of covariates representing pipe and environmental characteristics,
- b = coefficient estimated from a regression analysis.

Eventually a pipe will enter the wear-out phase, often after it has experienced two or more breaks in relatively close succession. Andreaou and Marks (1986) refer to this as the fast-breaking stage where pipes experience multiple and frequent breaks and where there is no apparent trend of increasing or decreasing break rate with time. Breaks at this stage can be reasonably represented as poisson arrivals at a constant

Figure 5.1: Typical hazard function



A - Start-Up Phase (initiated at t_0)

B - Normal Operation Phase

C - Wear-Out Phase

Source: Bury (1975)

arrival rate, with break rate independent of time and the number of previous breaks. At this stage, the break rate among various pipes can be highly variable and is best captured through a regression-type model. Andreaou and Marks (1987) found the following exponential model to be appropriate:

$$p(x) = [(rt)e^{-rt}] / x! \tag{5.5}$$

where, $p(x)$ = probability of having "x" breaks in time period "t",
r = break-rate, estimated from the following regression:

$$r = e^{b_1 z_1 + b_2 z_2 + \dots + b_n z_n} \tag{5.6}$$

where, z_n = covariates reflecting pipe and environmental characteristics
b_n = coefficients estimated from the regression

As can be seen, the regression equations in this analysis are similar to those of equations 5.3 and 5.4. by Clark et al (1982).

The development of predictive models such as those outlined in this section is important in the rehabilitation decision process. Inputs on anticipated pipe behaviour are required to arrive at optimal replacement decisions as will be shown in the next section.

5.3. Decision Analysis

There are a number of methods currently used by utilities in making decisions on whether and when to replace or rehabilitate a water main:

1) General "Rules of Thumb"

2) Economic Analysis

3) Reliability Analysis

4) Physical Models

5) Hydraulic Performance

6) Field or In-Situ Inspections

The extent to which a utility uses one or a combination of these techniques varies widely. One or two techniques may be used in small utilities while combinations of all the inputs have been developed by larger agencies into replacement scoring systems which can be used to rate individual pipe sections for repair or replacement.

5.3.1. Rules of Thumb

The general "rules of thumb" is probably the most common method used, though it has severe limitations and can result in much less than optimum replacement schedules. Such techniques are typically based on the experience of the manager or operator and are characterized by usually being quite simple and sometimes arbitrary, for instance replacing all pipes older than 40 years, replacing all pipes with at least two breaks, replacing all asbestos cement pipes, or replacing all pipes under future road improvements. While these rules are often justified by some underlying economic or health premise, they are not always arrived at in a rational manner and can sometimes lead to sub-optimal decisions.

Common "rules of thumb" based on replacing individual pipes by age, simple breakage rules, or "gut feelings" have been discounted as inefficient by many authors. Andreaou and Marks (1987) note that the probability of a break depends on many factors other than time since installation (e.g. pressure, corrosivity, land development, period of installation, and stage of deterioration) and that for pipes in the fast-breaking stage, the breakage rate is actually independent of age nor previous breaks. In the case studies investigated, Andreaou and Marks (1987) found that for pipes in the slow growth stage, replacement decisions based on simple rules of thumb, such as replacing all pipes with two previous breaks or replacing all pipes over 65 years old, would only reduce the breakage rate by at most 25 percent, while the replacement of all pipes with a failure probability greater than 5 percent, as derived from the statistical analysis, would result in a 40 percent reduction in breakage.

Another "rules of thumb" example relates to the health concerns of A.C. pipe which have not proven conclusive and in many ways are in doubt. The perception is that asbestos fibres cause cancer when inhaled and must be carcinogenic in general. In the U.S., the EPA has seemingly acted on this perception and applied it to water quality guidelines. Still, unless there is first some concrete evidence that the fibre concentration is significant and, secondly, that the A.C. pipe is contributing to the fibre concentration in the distribution water, perhaps resources and replacement dollars could be better spent on mains which have high breakage incidents and which on a regular basis are responsible for much higher real public health concerns. That is not to discount the genuine concern regarding health factors, but it does illustrate how uncertainty can overemphasize some concerns.

5.3.2. Economic Methods

There are both direct and indirect costs resulting from main breaks. The direct water utility costs include the repair and emergency crew costs, water treatment and pumping costs with lost water, and damage claims. Indirect costs include overhead and emergency police and fire protection during break, damage costs to consumers not reimbursed by the utility, service disruption costs, costs imposed on affected adjacent utilities, and the cost of traffic and public transportation disruption (AWWA 1989).

Economic methods base replacement of a main on a comparison of current replacement and maintenance costs to the sum of current repair costs and future costs of repair and service disruptions, discounted to the present. Replacement is justified when the money spent on repair is greater than the amortized replacement value of the main in the ground or when the total costs of repair and replacement are minimized (see Figure 5.2).

The optimal replacement time is typically given by:

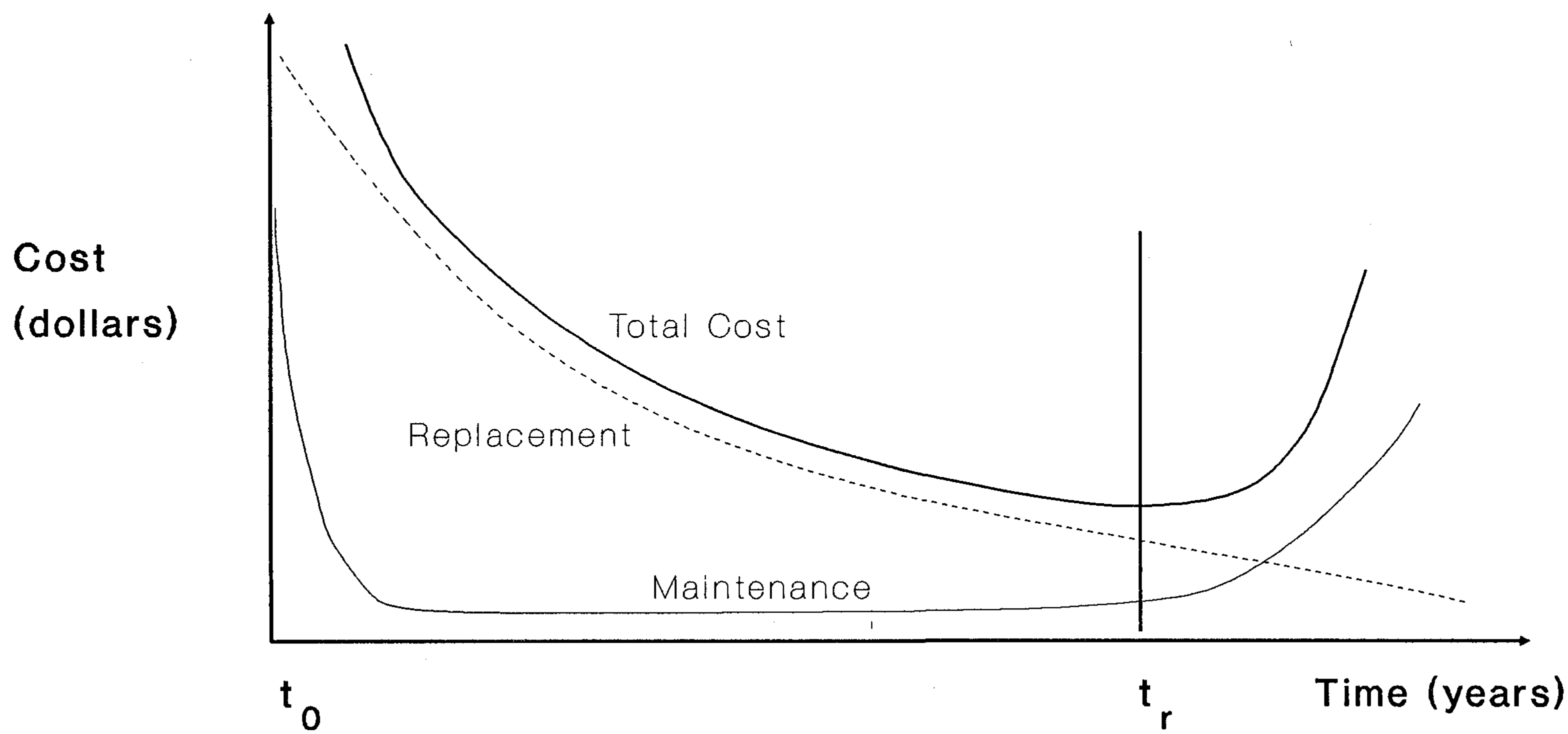
$$t^* = \ln [C_r \ln(1+r) / C_b E_o] / \ln(1+g) \tag{5.7}$$

where,
- t^* = optimal replacement time,
- C_r = cost of replacement,
- C_b = cost of repair,
- Eo = expected number of breaks during base year,
- g = estimated break growth rate,
- r = discount rate.

Predictive models such as presented earlier by Shamir and Howard (1979) are used to estimate future breakage trends. Andreaou and Marks (1987) note that pipes in a slow breaking stage rarely require replacement by such economic criteria and suggest that many of the pitfalls which assume exponential or linear increase of break rates with time could be avoided.

Similar economic criteria are used to determine the timing for pipe renovation, which involves cleaning the tuberculation off the interior of a pipe with a scrubbing "pig" and then cement mortar lining the interior of the pipe to prevent further corrosion and tuberculation build-up. Andreaou and Marks (1987) suggest that a pipe should not be renovated if it is expected to develop a large number of breaks in the future. As the effects of renovation on breakage rates, while not yet documented, are undoubtedly small. Thus a pipe should be replaced if the cost of replacement is less than the cost of

Figure 5.2: Optimal pipe replacement scheduling



t_0 = initial installation

t_r = optimal replacement time

rehabilitation plus the cost of expected repairs after renovation:

$$C_r \le C_{reh} + \sum_{t=1}^{n} [(C_b E_o (1+g)^t)/(1+r)^t] \tag{5.8}$$

where,
- C_r = cost of replacing a pipe,
- C_{reh} = cost of rehabilitation (or renovation),
- C_b = cost of break repair,
- E_o = expected number of breaks during the base year,
- g = break growth rate,
- r = discount rate,
- t = time increment.

Walski (1982) provides an economic based technique to determine how to renovate lines fed directly from pumps, where there is the option of increasing pumping capacity to increase the pressure or renovating the main to increase the "C" factor. The method is not appropriate for small distribution lines which are sized for fire flow and are fed directly from storage tanks, where it is impossible to significantly increase the head. The method entails renovating a line only when the cost for rehabilitation is less than the extra cost for pumping energy and additional equipment (ie. pumps) through the reduced "C" pipe.

5.3.3. Reliability Analysis

Reliability analyses on new systems are rarely done, primarily because of the lack of a universally acceptable definition or measure of the reliability of water distribution systems. Design techniques have been developed using optimization methods, but most still have strict limitations and are based on normal loading conditions such as peak hourly demands or peak daily demands. Very little work has focused on abnormal or emergency loading conditions such multiple fire demands, pump failure, control valve failure, power outages, and broken links which can be associated with normal daily operation or infrequent events such as earthquakes. No "optimization-reliability" evaluation or design technique with general application has yet been developed (Mays 1989). However, the study into reliability of existing systems especially in seismic zones has grown, especially since the 1971 San Fernando earthquake and even more so since the 1989 San Francisco earthquake. In North America, there are no seismic codes related to water systems, though guidelines have been developed based on past experience.

With respect to normal system operation, Andreou and Marks (1987) suggest that reliability criteria would play a more important role than economic criteria in determining repair versus replacement strategies. Failure probabilities obtained by the hazard models can be used to directly estimate the reliability of given links in a network, while at the same time they represent a single quantitative measure of the risk based on the interactions of factors like age, break history, operating and environmental characteristics. At the networks level, the implications of a break would also have to include the evaluation of a hydraulic model to assess the implications at all points on the system. For further developments in reliability analysis, the reader is directed to a recent publication by the ASCE (1989). However, as O'Day (1984) points out, there are still a number of legal and technical matters to be cleared up before reliability and risk analysis are widely accepted. It must be remembered funds are limited and prioritizing may have to be carried out. O'Day suggests in areas of high probability of failure but low risk, leakage control should be increased while in areas of high risk, the replacement of mains should be accelerated to reduce the impact of main break damage.

5.3.4. Physical Models

The estimation of remaining structural life in a main is typically used in large utilities where human and technical resources are sufficient and pipe corrosion is a major problem. Physical models are developed to estimate the pipe age using deterministic rather than probabilistic means. Typically the problem is well defined and the mechanics of the deterioration process being modeled are relatively well known. Three investigations by the City of Vancouver, the U.S. Army Corps of Engineers, and the City of Philadelphia involved modelling the physical processes associated with pipe corrosion and are outlined in AWWA (1986). The Vancouver and Philadelphia studies both focused on estimating the "time to failure" of old grey cast iron water mains while the U.S. Army study focused on gas distribution mains.

In 1978 the City of Vancouver initiated a program to determine the remaining service life of 68 kilometres of cast iron mains installed in the 1900s (AWWA 1986) and later developed models to incorporate steel pipe (Bratton et al 1986). The basis of the model is Rossum's general equation for predicting maximum external pit depths (Bratton et al 1986):

$$P = Kn\,(10 - pH)^{n}\,p^{-n}\,t^{n} \tag{5.9}$$

where, P = depth of pit (mils),
Kn, n = aeration constants,
pH = measure of soil acidity,
p = soil resistivity (ohm-cm),
t = time (years).

Internal corrosion of unlined steel and cast iron pipes was estimated using the following (Bratton et al 1986):

$$P = 45\,t^{1/3} \tag{5.10}$$

where, P = depth of pit (mils),

t = time (years).

A series of 30 theoretical "pit depth versus time" curves were developed and calibrated using field data for various conditions any particular pipe may be exposed; curves were developed for soil resistivity ranges from 3,400 to 900,000 ohm-cm, pH ranges from 4.6 to 9.4, and soil aeration from poor to well aerated. Field data was collected from various sources: break records and staff interviews identified problem areas in the City; potential stray current sources were evaluated; water analyses were done to determine corrosive properties; over 5,000 soil resistivity measurements were taken to identify corrosive areas; soil sample analyses at main depth were done to determine pH, sulfides, moisture content, and redox potential; and 20 mains were physically inspected for pit depths and uniformity of wall thickness (AWWA 1986, Bratton et al 1986). The study found that actual pit depths were on average about 9 percent lower than the theoretical predicted.

The practical application of the model involves determining the age, wall thickness, soil type, and loss of wall thickness due to internal corrosion for a particular pipe. The minimum wall thickness allowed for the pipe is then determined from the forces and stresses on the pipe as well as the pipe's material properties; for instance the structural strength of a cast iron pipe is directly dependent on the wall thickness. The actual versus minimum wall thicknesses are compared and the difference is applied to one of the theoretical curves to derive the "time to failure". Once any pipe has reached its theoretical "time to failure" it is put on a replacement program (Bratton et al 1986).

Application of such a model requires intensive field investigation but has the advantage of including factors that directly have an effect on the structural integrity of a main. Unfortunately this model does not consider external loads nor bedding related structural conditions (AWWA 1986).

The U.S. Army Corps of Engineers Construction Engineering Research Laboratory (CERL) developed a model which also estimates the depth of external corrosion of cast iron mains and the "time to failure" using a corrosion status index (CSI). The index is a numerical rating between 1 and 100, with 1 representing a completely deteriorated main and 100 representing a newly installed one. The CSI is calculated as follows:

$$CSI = 100 - 100\,(PAV / T) \tag{5.11}$$

where, CSI = corrosion status index
PAV = average corrosion pit depth (inches)
T = thickness of main wall (inches)

Gas mains were found to leak when the CSI dropped to 30, which correlates to the average depth being 70 percent of the original wall thickness. The pit depth can be determined by either physically digging up the main and measuring, through electrical polarization techniques, or through mathematical model estimates. Estimates of the CSI have also been developed based on factors such as the rate of pit growth with time, prediction of maximum from average pit depths, average number of years to leaks, and the effects of main coatings as well as soil pH, resistivity, sulfides, and moisture. CERL has developed a computerized pipe management program for low pressure gas mains, and with modifications to account for internal corrosion and higher operating pressures, could be applied to water pipes.

The Philadelphia Water Department has developed a prototype water main condition assessment model (CAM) which estimates the internal and external loads and the internal and external corrosion losses, then predicts the remaining wall thickness and computes the safety factor. The system was developed for older grey cast iron mains which represent the majority of the City's distribution system. Because the model was developed for grey cast iron pipe, which is structurally rigid, it can not be applied to ductile iron pipe. The model includes eight modules: pipe characteristics, environmental conditions, corrosion losses, estimated loads, maximum allowable loads, design loads, safety factors, and structural condition rating.

Each module has a variety of inputs and outputs. The "pipe characteristics" module includes the input of pipe diameter, age, length, depth, original wall thickness, material, joint type, breaks, working pressure, and cleaning and lining history. The "environmental conditions" module includes the input of physical conditions that might have an impact on the life of the main such as leakage, number of abandoned services, pavement type (rigid or flexible), proximity to stray current (ie. rapid rail substations, or d.c. rail). The "corrosion losses" module estimates corrosion losses for internal, galvanic, and electrolytic corrosion based on modifying the City's average corrosion rates for the environmental conditions. The "estimated loads" module assesses the surge pressure, external loads, truck loads, thermal stresses which result from the environmental conditions. The "maximum allowable loads" module determines the maximum ring load, pressure stress, and beam moment the pipe can withstand based upon its unit strength and remaining wall thickness. The "design loads" module determines the stresses caused by five standard load scenarios as outlined in AWWA C101-67. The "safety factors" module estimates the individual safety factors by comparing the computed stresses derived from the design loading to the unit strengths or maximum loads at failure for seven conditions with varying internal and external pressures and loads. The "structural condition" ratings are based upon the minimum of the seven safety factors: mains with safety factors less than 1.0 are classified as "questionable", while mains with safety factors greater than 1.0 are classified as "satisfactory".

As can be expected, the previously mentioned models can only be considered as prototypes as every utility has very site specific characteristics and problems. The above models should be used as guidelines, but must be calibrated and verified using local data to assure that all results are realistic.

5.3.5. Hydraulic Performance

While structural considerations associated with the previously described descriptive, predictive, and physical models are extremely useful in assessing a water distribution systems structural condition, many utilities rely on hydraulic performance criteria rather than structural criteria to assess the condition of their systems. Flow and pressure are the main performance criteria whereas breaks are the main structural criteria. Although both structural and hydraulic criteria can be used mutually give the most reliable assessment of system condition, the ease and availability of hydraulic programs makes them most often and in many cases exclusively used, especially in smaller utilities where neither the records nor the resources required to develop a structural model are readily available. Structural models are typically limited in sophistication to the utility deciding from experience that a main is experiencing too many breaks and should be replaced.

The advent of the personal computer has meant that hydraulic models which can model a communities water system in a variety of consumption and future scenarios are easily affordable and relatively simple to operate. Programs such as WATER [1] and

---

[1] WATER - Copyright Municipal Hydraulics

SDP [2] allow the user to input pipes, nodes, pumps, and control valving to simulate entire water systems. Once input, limitless demand scenarios can be run and re-run, each taking only minutes versus what used to take hours manually. The output can then be calibrated with actual flow and pressure measurements obtained at access points throughout the system, such as at fire hydrants. Any sections of the system which show reduced flow capacity or large pressure drops can be readily identified. Bottlenecks which can reduce fire fighting potential or future system expansion can be found; pipes suspected of having undergone tuberculation can be verified and scheduled for cleaning; zones of negative pressure which could be a source of system contamination or potentially produce pipe collapse can be catalogued and rectified. Still these programs represent only one of the tools required to properly manage water distribution systems.

5.3.6. Field or In-Situ Inspections

While network models can help detect sections with gross capacity deficiencies, more specialized techniques are required to pin-point the more subtle deficiencies such as slow leaks and localized reductions in wall thickness. The technologies involved do not involve excavation but rather are from an analysis with the pipe "in-situ"; as such, detection methods are often more of an art than an exact science.

A number of devices and technologies developed by the oil and gas pipeline industry can and have been successfully applied to water pipelines. Graf (1989) outlines how ground penetrating radar has been used successfully to detect leaks in gas mains. Price and Wolf (1989) outline and review a number of techniques including visual

---

[2] SDP - Copyright Charles Howard & Associates Ltd.

inspections, above ground electrical surveys, acoustical methods, proof testing, and T.V. inspections. Above ground electrical surveys involve the measuring of electrical potentials, the electrical resistivity of the soils or the localized leakage of an induced current from a pipeline to detect coating damage or areas of potential corrosion. Such surveys rely on a great degree of interpretation and are most effective if carried out systematically over a large area. Acoustical methods include sonic and ultra-sonic detection of cracks and voids; while effective they can be hampered by noisy pipelines or high background noise in the underground conditions.

Proof testing by isolating, pressuring up, and measuring the pressure drop of a section of pipe is also very effective in detecting leaks, though over long stretches it can be difficult to locate the leak. In addition, the pipeline must be put out of service temporarily.

The running of remotely controlled video cameras inside small diameter pipes has for years been standard practice with sewer lines, though it has had only limited success with water lines. Water lines lack the easy access points such as manholes and are often riddled with obstructions such as valves. The resolution of the video cameras is usually not great enough to allow location of the small cracks usually responsible for slow leaks and again, the water line must be taken out of service to allow a video inspection. Visual inspections from inside a pipe can only be carried out in large diameter mains; the mains must be shut down and access gained to allow inspections.

Instrumented pigs have also proven popular in the oil and gas industry, though as VerNooy and Jordan (1983) point out the technology is still developing. Instrumented pigs include any self-contained device which travels through a pipeline propelled by the flow of fluid carried in the pipeline. They measure various parameters and record the data for later evaluation (ie. pipe geometry, leaks, wall thickness, etc.). With the advent of newer, stronger pipe materials, pipe wall thicknesses have decreased resulting in significant material savings. However, as VerNooy and Jordan (1983) point out, the reduced wall thickness has meant that pipe breaks now occur after many cycles of operational stress reversals rather than in the initial hydrostatic tests. Thus the need for good leak detection is becoming more rather than less. VerNooy and Jordan (1983) and Allman and Dilay (1983) list a number of such "smart" pigs used in the oil and gas industry: calliper pigs can continuously measure the inside diameter of a pipe; leak detection pigs can measure pressure, temperature, or material differences at leak locations. Although promising there are inherent of characteristics which make application of these techniques difficult; water lines have many service connections which can be wrongly identified as leaks; ultrasonic leak detection pigs are promising but again may be subject to interference in noisy or dirty pipes; a variety of miscellaneous pigs which can video, measure pressure and temperature, flow detection and magnetic flux flaw detection have also been developed though their application to water distribution systems is not yet extensive. Most of these techniques would best be applied to long, straight transmission mains rather than the congested networks of distribution mains.

To avoid the perils of crisis management which leads to poor customer service and unnecessarily high repair costs, regular leakage surveys and water budget calculations can be based on an inventory assessment in larger utilities or on a regular interval basis such as ten year periods.

5.4. Mitigation Techniques

The development of municipal technologies versus other technologies in our modern world has not been rapid due in large part to the lack of competing groups and the aversion to risking new technologies among municipally run utilities. Within the water distribution industry the two main upgrading technologies used today are by no means new; a deteriorated water main can either be cleaned and mortar lined or replaced. Cleaning and lining is typically limited to those pressure and flow characteristics which can still be lined without significantly reducing the hydraulic capacity below the required demands. Replacement of a pipe is still by far the most widely used method of improvement. It is largely carried out using conventional open-cut techniques with an excavator such as a backhoe supplemented by human labor to assist in the placing and aligning of pipe and the compacting of backfill. New "trenchless" technologies have developed in recent years to take advantage of the existing "hole in the ground" but for the most part practical applications have been in the gravity sewer industry. Still trenchless techniques hold promise with pressurized water distribution systems, at least on long lengths with few obstructions such as valves, elbows, or service connections.

Apart from the supply side solutions aimed at improving the structural components of the distribution system, non-structural techniques are also carried on exclusive of the pipe. Typically they involve operational techniques aimed at reducing ever increasing system demands through water conservation methods. While effective in the longer term, such techniques do not solve the short-term problems of leaking, deteriorating pipes.

5.4.1. Pipe Replacement

The open trench method involves the excavation of a trench, laying the pipe within the excavation, and backfilling. The width of trench is governed by safety regulations aimed at protecting the workers in the trench. Minimum excavation side slopes combined with the depth required will set the width of surface disturbance. For an installation depth of 2.5 meters, the width of trench at the surface can vary from 4 to 6 metres, with the entire disturbed width being approximately double this with a spill pile. Such excavation can effectively shut down an entire roadway. Shoring the excavation walls can minimize the excavation width, but the operation can still close one to two lanes of traffic and significantly disrupt access to commercial or residential establishments adjacent to the street.

When calculating the overall cost of a project, a utility typically includes the direct costs which will have to be paid out. Such costs include the actual costs of construction plus any third party costs such as compensation for disturbance of business, the cost of service diversions, or the cost of structural damage due to trenching in poor soils or areas with a high ground water table. What typically does not enter the cost analysis are the intangible or indirect social costs which are borne by the community but are not paid for by the utility. Such costs include those associated with traffic delays, reduced pavement life, additional wear on diversion routes, and the environmental effects of increased noise, vibration, dust, and unsightly excavation conditions.

Trenchless technologies which have developed since the mid-1970s aim at minimizing or eliminating altogether the need for such disruptive surface excavations and at satisfying the implicit "Do Not Disturb" sign now being posted by society (Fedotoff et al 1990). Actual construction costs associated with trenchless methods often exceed those of conventional methods. However, the main argument for the use of trenchless technologies lies in the significant reduction of the indirect costs associated with open-excavations. In a recent report to the FCM outlining guidelines for the use of trenchless technologies on Canada's sewer infrastructure, various studies were identified which found the social costs associated with traffic delays were estimated at 1.25 to 2.6 times, and in one case 10 times, the capital construction costs of the sewers (City of Winnipeg 1991). The report sites a case in the Barbados where, even though the capital costs associated with the conventional method were 25 percent lower, upon inclusion of the social and environmental costs which would have negatively impacted on the tourist industry and the local residents, the trenchless technique was found to be more cost effective.

Trenchless technologies are considered to be in the developmental stages in North America, having developed largely in Japan, Germany, and the United Kingdom (City of Winnipeg 1991). A number of "NO DIG" conferences have been held in North America since 1985. The ASCE and the City of Montreal have included trenchless techniques in their sewer rehabilitation manuals, and a number of projects have successfully utilized the methods. In Toronto a 430 metre length of 750 mm diameter storm sewer on Keele Street was successfully completed for just under $1,000,000 during the winter of 1990/1991 (Vardin 1991). The project involved poor soils and a high water table which would have required dewatering and well points had the conventional method been employed. The contract tender allowed one of three methods: open cut, conventional tunnel, or microtunnel. The low tender proposed use of the microtunnel technique, a result which signals such techniques are becoming competitive from a capital cost standpoint with conventional techniques. The project minimized traffic disruption, maintained access to all neighborhood driveways, reduced truck traffic through reduced excavation volumes, minimized noise as only small portions of pavement had to be broken up, and saved $60,000 in pavement cut repairs over the open-cut method. In addition, job safety and working conditions were much improved over conventional methods. While Vardin (1991) notes the method may not be applicable to every situation, it is especially appropriate to deep (> 6 metres) excavations or where traffic disruptions would be unacceptable.

A number of centres have made trenchless techniques common in their rehabilitation programs. In Singapore for instance, trenchless techniques are the only ones allowed for sewer construction rehabilitation in built-up areas (City of Winnipeg 1991). In North America, the City of Houston has been the main proponent of trenchless techniques. By early 1990, the City had installed over 24 kilometres in four years using the microtunnelling method. This represents over 80 percent of the total length utilizing this technique in the U.S. (Fedotoff at al 1990).

While the trenchless techniques offer significant improvements over traditional methods, their application has been limited more to gravity sewers rather than pressure distribution and transmission mains. Sliplining and cement lining techniques have remained the most common renovation methods, but have several disadvantages including loss of inside diameter and therefore hydraulic capacity. In communities which have a large number of small diameter deteriorating pipes which are already insufficient for fire flows, such techniques will not be useful. Probably the most promising technique for in situ replacement of cast iron pipes is by the bursting method which is especially suited to cast iron's brittle nature. Unfortunately, such methods are not as suitable to the stronger and more flexible ductile iron pipes.

Unlike sewer lines, water lines are more problematic with respect to such trenchless techniques. Water distribution systems contain obstacles such as valves and tight elbows and lack manholes for easy access. In addition, trenchless techniques still require that open excavations be carried out to allow reconnection of services. However, such techniques still hold promise though they will not solve the root of today's problems which is the political will and financial means to carry out such operations on a nation-wide and systematic basis.

5.4.2. Trenchless Methods

Trenchless methods includes a wide variety of techniques aimed at the rehabilitation and renewal of pipe structures. Rehabilitation techniques aim at leaving the existing pipe in place and improving the inside surface of the pipe. Renewal techniques focus on removing, displacing, or abandoning the existing pipe in favour of a new pipe.

Rehabilitation techniques for sewers typically involve pipe lining methods and include (City of Winnipeg 1991):

1) Insituform (polyester resin) lining
2) Fibreglass lining
3) High density polyethylene (HDPE) lining
4) Phenolic resin lining
5) Reinforced mortar coating
6) Polypropylene lining

Insituform lining is a patented process and product where a sock-like product comprised of a polyester needle felt tubing saturated with a thermosetting resin is pulled into an existing pipe following an initial pipe inspection and preparation. The "sock" is then pressurized into final shape with cold water which is subsequently heated to initiate the thermosetting reaction which creates a new pipe within the old.

Fibreglass lining is used in structurally sound sewers with diameters typically greater than 1100 mm. Segmented fibreglass reinforced plastic liners are inserted and mechanically jointed within the pipe. Any spaces between the liner and the pipe are then filled with grout.

High density polyethylene liners involve the installation of continuous lengths of HDPE pipe with an outside diameter smaller than the inside diameter of the existing pipe. A variety of installation techniques are used including insertion into an existing pipe of a collapsed or smaller diameter PE pipe which is subsequently heated or pressurized to conform to the existing pipe wall.

Phenolic resin lining involves a technique similar to mortar lining which is commonly done on water mains. The technique involves first scraping and cleaning the interior wall of a pipe to be treated and then spraying the surface using centrifugal application of a phenolic resin rather than a mortar. As with mortar lining, this technique is used on pipes which are still structurally sound.

Reinforced mortar coating involves the centrifugal application of a mortar to a prepared interior surface of a pipe followed by the insertion of steel reinforcing and a final application of mortar to hold the reinforcing in place.

Polypropylene lining is similar to that of HDPE lining, though the differing liner material characteristics make each suitable to slightly different conditions.

Trenchless techniques aimed at replacing the pipe in the ground rather than improving it are quite varied and include the following (City of Winnipeg 1991):

1) Tunnelling
2) Pipe Jacking
3) Microtunnelling
4) Auger Boring
5) Impact Ramming
6) Directional Drilling
7) Impact Moling or Pipe Bursting
8) Jet Cutting
9) Thrust Boring
10) Wet Boring
11) Slurry Boring

Tunnelling has been used for decades and involves the large diameter installations with secondary liners. Tunnel sizes are such that personnel may easily enter.

Pipe jacking also involves the use of large diameter installations. A rigid pipe is jacked into place, usually with hydraulic equipment, just behind boring or augering equipment at the face of the excavation. Waste excavation is hauled via a conveyor back through the pipe.

Microtunnelling is one of the techniques developed in recent years which allows the installation of small, non-personnel entry sized pipe using a remote controlled excavation, mucking, and steering operation. Standards and techniques are becoming quite well developed. Stein et al (1989) provides a detailed reference for this technique.

Auger boring is a common method for railway and highway crossings involving a horizontal excavation without remote steering. A steel casing is typically installed to allow insertion of the distribution pipe.

Impact ramming is similar to the auger bore, except the steel casing is rammed into place with pneumatic equipment rather than bored.

Directional drilling involves the horizontal excavation using remotely controlled steering equipment. It is distinguished from microtunnelling in that it involves the smaller diameters of non-entry pipes, typically 150 mm or smaller.

Impact moling and pipe bursting involves the insertion of a conical device into an existing pipe. The device fragments the existing pipe and then displaces the fragments into the surrounding soil. The insertion pipe typically follows immediately behind the operation and may be equal or greater in diameter than the original pipe size.

Jet cutting is a variation of the directional drilling method involving the use of a hydraulic jet to excavate the hole.

Thrust boring, wet boring, and slurry boring are variations of the auger boring method.

Fedotoff et al (1990) provides an excellent summary of the current trenchless techniques including the typical pipe diameters, spans, and materials associated with each technique as well as the accuracy, applications, and examples of each.

While physical pipe rehabilitation techniques are the most obvious means of mitigating the current problems, operational techniques can aim at reducing the demands on overworked systems or conversely utilize under-worked systems to reduce the need and costs for expansion. The premise of such techniques is that systems should be utilized to their optimum and that demand on such systems should be reasonable. Thus the concepts of demand management, which include conservation and realistic, equitable price structures, fall into this category. In addition, effective land use planning with the objective of utilizing the existing infrastructure to its optimum level can be a component.

5.4.3. Demand Management

While the techniques associated with the efficient and effective upgrading of the pipes in the ground are valuable, they really only represent half the long term solution.

Rather than focusing on repairing the supply systems, demand management focuses on optimizing consumption and peak flows which run through the system. It is based on an implicit philosophy that the amount of water a consumer uses should not be open-ended and that policies should be put in place which discourage such a case. Municipal water systems would represent only one component of an overall scheme which would include other major water uses such as irrigation, industrial, and power generation.

Canada does not have an over-abundance of fresh renewable water. Canada occupies 7 percent of the world's land mass and nearly an equal proportion of its renewable water at 9 percent, but of this about 60 percent drains north and 90 percent of the population is within 300 kilometres of the southern border (Environment Canada 1987). In essence, while Canada is not short of water, most of it is not necessarily where it is needed. This situation is made worse by the fact that while Canadians enjoy the among the lowest prices in the world for water, they are among the highest consumers per capita.

Demand management stresses the reduction of unrealistically high consumption rates and a more effective distribution of human, financial, and natural resources within the water sector. Traditional water system development has largely hinged on a view that water is a requirement to be met rather than a resource to be conserved. As Postel (1985) argues:

> "Planners have typically projected future water demands based on the historical rate of growth in per capita water use and the projected population. They then plan to meet this estimated demand by drilling more wells or building new reservoirs, and expanding the capacity of their water and wastewater treatment plants. Rarely have planners focused on reducing water demand as a way to balance the long term supply/demand equation."

The tools required for an effective reversal of this trend vary widely and would target a broad range of groups, from the individual consumer in their home to the utility itself to the local, provincial, national, and even international political forums. Tate (1990) summarizes the techniques into three basic groupings:

1) Economic Techniques
2) Structural and Operational Techniques
3) Socio-political Techniques

5.4.3.1. Economic Techniques

Economic techniques as applied to the municipal water management aim at using water pricing policies to influence the level of water demand. The techniques are centred around the economics of price elasticity. In general, the higher the absolute value of elasticity, the greater a given change in price will have on demand. The demand curve for domestic water is inelastic over the initial quantity of water used, meaning any price changes over this range of consumption will be very ineffective at reducing the water demand. Intuitively this makes sense as the initial water used in a household is considered essential to life. Above this, as water demand increases, the water uses become less essential and the price elasticity of demand increases. Water pricing methods can have the greatest impact in the form of reduced demand with uses which are both a highly consumptive and highly elastic such as lawn watering. Tate (1990) notes that lawn watering accounts for 30 percent of total domestic usage and can have elasticities in the order of - 1.0, meaning a 50 percent increase in the price for water would result in approximately a 50 percent decrease in consumption. Some typical price elasticities related to water supply can be found in Table 5.3.

Table 5.3: Typical residential price elasticities

WATER USE		ELASTICITY
Residential (composite)		- 0.225
Domestic	- in-house	- 0.260
	- lawn watering (western Canada)	- 0.703
Average Day		- 0.395
Maximum Day		- 0.388

Source: Tate (1990)

While the results of pricing changes may vary considerably among communities, the information presented does show some significant savings could be realized. As Tate (1990) emphasizes "Realistic water pricing, in the sense of recovering the full costs of water infrastructure, including repair, upgrading, and expansion costs, is the key factor in establishing demand management as a major tool in managing water resources."

Currently, not only the price but the price structures are thought to contribute to the high demand for water in Canada. Flat and declining block rate structures do not promote conservation and actually promote waste, as the consumer is paying either no more or less per unit volume used respectively for increasing volumes of water Tate (1990) notes that in Canada, of the 591 residential rate structures surveyed in communities, 442 were flat or declining block representing 75 percent of the total; of the 532 commercial rate structures surveyed, 357, or 67 percent, were also flat or declining block. The remainder included constant unit rates, which charge the same per unit regardless of volume used, and increasing block rates, which charge more per unit for larger volumes of water used. Increasing block rates, which are considered to be the best from a conservation view-point, were incorporated into less than 2 percent of the total commercial or residential rate structures.

Tate (1990) goes on to argue that low water prices and rate structures which promote inefficiency and waste result in the undervaluing of the water resource. Such undervaluing has hindered technological advances within the water industry and Tate concludes that realistic pricing would make savings due to technological improvements more valuable, thus prompting a greater emphasis on such improvements. The basis for such a realistic water rate structure would:

1) assure no revenue shortfall,
2) meet an efficiency criterion and treat customers in an equitable manner.

Tate suggests a two-part tariff, with a fixed charge to cover overhead and administration to be shared by all customers, and a constant commodity charge per unit of use, based upon the marginal cost of water supply and theoretically meeting the efficiency criterion.

The mechanism required to implement realistic pricing for the water commodity is the water rate schedule. Water demand management focuses on making water rate schedules reflect the true value of water and recovering the true costs which are incurred when delivering it. There are two basic types of water rate structures which are used by municipalities and other water agencies: flat rates and volume based rates.

Flat rate schedules require no metering as rates are fixed, regardless of the customer or the usage, and are generally based on covering operation costs. Flat rates contribute to the greatest amount of wastage and excess demand since the marginal price of water is zero (price of and additional unit of water over and above current use), thus there is no incentive to conserve. In the 1986 survey across Canada, 47 percent of the residential schedules were flat rate and were concentrated in smaller urban sized groups (Tate 1989).

There are three main types of volume based rate structures a community can adopt: constant rate, declining block, and increased block. All three types require metering of the consumers water, but not all are effective at promoting conservation. The constant rate structure charges a fixed rate per unit volume of water regardless of amount used. Declining block rates have successively reduced unit prices for higher "block" volumes of water consumed. Increased block rates have successively increasing unit prices for higher "block" volumes of water consumed. The volume of these blocks are set locally and can vary by class of consumer (eg. commercial, residential). Of the three methods, the declining block is the least effective at encouraging conservation, yet it is used in 52 percent of the residential rate schedules surveyed in 1986, while increasing block schedules, which are the most effective at promoting conservation, are used in only 2 percent of the surveyed schedules (Tate 1989).

But the effectiveness of rate schedules can not be compared on the criterion of conservation alone. The American Water Works Association (AWWA 1983) recommends that rate making practices be assessed against the four criteria of:

1) cost recovery
2) equity
3) economic efficiency, and
4) local acceptability.

Cost recovery includes the municipalities effectiveness at recovering the complete cost of maintaining, operating, and upgrading their systems through water rates.

Equity, though a somewhat ambiguous concept to define, basically incorporates the need to assess whether the consumers are being charged in proportion to their received benefits. Based on the equity criteria, the AWWA recommends declining block rates, as administrative costs which are incurred by all consumers are recovered in the higher cost initial blocks. However, Tate (1989) argues that other interpretations of the concept of equity can result in flat rates, where everyone is charged equally, or increasing blocks, where the extra system capacity required by large users is paid for by these users through the higher rates charged in the increasing blocks.

The economic efficiency criterion states that a systems must meet its given needs at the lowest cost. Tate (1989) points out that both flat and declining block rates fail this, as the marginal cost of water is zero or declining, thus producing overuse and artificially high system costs over time.

The final criterion, local acceptability, is probably the most important factor in the setting of rates and accounts for the widest variability in rate schedules across Canada. This is where the politics of local government comes in, as most municipalities choose the more acceptable pricing schemes such as flat rate or declining block, which are intuitively simple and perceived to be most equitable (Tate 1989).

There is a broad variation in rate structures and the resulting prices across Canada. Volume based rate schedules are common on the Prairies, accounting for 86 percent of the residential schedules and 95 percent of the commercial. To illustrate the effects of this on price, the mean price for 35 cubic meters of water is only $7.97 in Newfoundland and $31.91 in Manitoba. As can be expected, water rates are generally much higher on the Prairies than in the east or on the coasts (Tate 1989).

5.4.3.2. Structural Techniques

Structural and operational techniques include metering, retrofitting, using dual systems, and repairing infrastructure leaks for example. In Canada, only about 50 percent of connections to municipal water systems are metered, a great impediment to instituting pricing schemes based on water use. Based on an estimated 6.7 million connections in Canada, this would mean over 3 million meters would have to be installed at a cost of between $600 and $700 million dollars (Tate 1990). Tate feels this would be a good value compared to the $8 to $10 billion required for current infrastructure repair and upgrading and when coupled with price re-structuring would result in significant cost benefits to communities. Several cases have shown water metering and realistic pricing to result in reductions in water use by 15 to 30 percent (Flack 1981, Loudon 1986, Davey 1987).

Retrofitting high water use devices such as shower heads and toilets with water saving devices also falls under this category. Such techniques have been shown to save an average household 20 percent in water consumption over conventional devices and up to 40 to 50 percent on individual devices such as low-flow showers (Robinson 1980, Barclay 1984). In addition the energy savings associated with heating the water can be substantial (Postel 1985).

Another useful structural development is the dual water system which splits the household water into two separate sets of piped supply, one potable for cooking, drinking, and other functions requiring high quality water, and one sub-potable for sanitation, irrigation, or fire protection. Such systems can save on the water treatment chemicals required for potable water. "Grey water" systems which recycle water kitchen and shower water for use in flush toilets and lawn irrigation have been found to save up to 39 percent over conventional systems (Haney and Hagar 1985).

5.4.3.3. Sociopolitical Techniques

The final category of demand management tools which Tate (1990) outlines are the sociopolitical techniques, the major ones being:

1) water pricing
2) public education
3) privatization

Water pricing, as outlined earlier, forms the backbone of any demand management policy and works toward self-sufficient utilities rather than ones supplemented by general tax revenues.

Public education through the media, educational institutions, and action groups is an important factor in bringing such programs to fruition. The most difficult change will be a change in attitudes and a realization that water and the infrastructure associated with it is valuable. Robinson (1980) estimates that education programs alone could account for a 10 percent decrease in consumption.

Privatization is a third technique being investigated in North America to assist ailing municipal utilities. Tate (1990) notes that some studies have shown that privatization could save municipalities 10 to 30 percent. Proponents argue that the private sector would be more efficient and effective at managing and improving systems, and more importantly would be more effective at raising capital than the public sector. Precedence are cited in France where private utilities have operated systems since World War II which now serve over 60 percent of the French population. These systems have been operated efficiently and substantial innovation has been associated with the management and development throughout the years. Tate (1990) notes that, while not making an assessment of privatization within the Canadian context, a number of advantages and disadvantages can be found. The advantages for a municipality typically include a decrease in the financial burden, cuts in administrative costs, and the opportunity to take advantage of technological innovations. Disadvantages include the loss of direct control by municipal authorities, environmental quality control, and public ownership of water systems. However, Tate notes that some proponents stress that such disadvantages could be overcome through effective contract negotiations.

Water demand management in practice will not be without its problems. Current infrastructure needs require a significant amount of capital and new pricing structures will be required to assist in financing such. In addition, the costs associated with the supply of water are relatively inelastic to demand (Loudon 1986), and as such will not be reduced a substantial amount even for significant reductions in demand. Given that the major financing requirements will not decrease in the short term, any program which is effective at reducing demand will not necessarily be effective at reducing the revenues required by the system. Since charges on consumptive flows are the only means a utility has to raise revenues, it is reasonable to conclude that every unit decrease in demand must be accompanied by a similar increase in price to generate the same amount of revenue. To meet current capital requirements plus the additional requirements needed for upgrading, revenue levels must increase rather than decrease. To accomplish this, the average consumer will see an increase in their overall water bill regardless of their conservation effort and decreased consumption level. As Loudon (1986) notes, "Customers will understandably not be pleased to see their efforts rewarded with water bills which don't decrease." Loudon termed this entire situation the "conservation conundrum", and emphasized that this lack of real short-term financial reward to consumers can be an obstacle to the implementation of conservation programs aimed at longer-term benefits and consequently make municipalities wary of adopting them. As Tate (1990) notes these problems may require short-term financial assistance from senior levels of government.

Tate (1990) feels the practical application of water demand management based on the installation of water meters and realistic pricing mechanisms will lead to a greater desire to conserve. Depending on the magnitude of price increases and the elasticity of demand, short term water usage would fall by about 25 percent and level out around 15 to 20 percent in the long-term. Financial capital allowing repairs and leak detection would be generated, though in the short-term some temporary financial assistance to municipalities would be required to overcome the initial effects of reduced demand. Eventually, demand forecasts used in facility planning would be lowered, delaying or postponing the need for infrastructure expansion, and lowering the operation and maintenance costs as pumping energy costs and treatment and waste treatment costs are reduced. Tate hypothesizes that urban centres might become more dense as new developers and new developments become responsible for the full marginal cost of water supply. Eventually, with a more realistic value of the water resource realized, residents and industry would be prompted into more conservation conscious measures.

5.4.4. Land Use Planning

Undoubtedly the single most important factor influencing both short and long term infrastructure requirements is how people want to live in their community. How people want to live is nearly solely reflected in the communities' land use policies and prominent zoning classes, be they low density, sprawling, large lots carrying single family residences or intense high rise developments. As such, infrastructure in itself is a means, not and end, to achieving these policies and as such infrastructure development is nearly wholly determined by external factors.

Much has been written in planning about the efficiency of dense developments, especially residential developments and the savings which can be realized from reduced infrastructure requirements relating to transportation and utility services. Infilling of vacant lands within urban areas and increased subdivision densities can reduce water system requirements on a per capita basis. Theoretically, densification can increase revenues for a utility granted the existing system capacity is such that it can handle additional users. Undoubtedly, in small communities where densification could have the greatest impact there would be resistance toward intensified land use from residents who are typically living in the community for the very reason it is not as urban or dense. In the larger cities the potential for increasing densities varies, with many cities possessing densities which are already quite high. Still, infilling and increasing densities where possible while still retaining the character of a community can help alleviate some of the problems.

Revenues from development cost charges per meter of water lines installed can be increased from increased development densities. In some cases, the newer parts of existing systems could be densified to help pay for the rehabilitation of the older parts of the system. With proper planning, the older parts of the system could be rehabilitated to a point where they can support additional capacity and densification to eventually funds for other parts of the system. However, any increases in density must be handled with care so as to avoid straining existing systems which are already overworked or in a deteriorated state. This type of solution could work best in areas where the existing system does not immediately require significant rehabilitation, where sufficient capacity exists for domestic demand and fire flows, and where the community will accept it. Unfortunately, the latter citeria often dictates land use densities, and the issue of efficient water system management does not enter the debate.

Another major drawback to this approach when looking at the current situation is that it is a long-range solution and not a quick fix. It may require years of debate and a change in attitude for a community. In many cases it is likely people would rather pay higher water rates rather than have the character of their community changed significantly.

Still, densification is not a guarantee that it will solve the problem. Water distribution system deterioration still remains a significant problem even in the larger denser cities, where service densities can be 5 or 6 times those of smaller communities, but it can reduce the per capita impact of system rehabilitation when needed. It would still be beneficial for small communities to adopt this type of policy so that when system deterioration becomes significant in the next 10 or 15 years, the impact can be lessened.

CHAPTER 6: DEVELOPMENT OF A POLICY FRAMEWORK

6.0. Goals of a Comprehensive Capital Works Management Policy

The current infrastructure funding crisis requires a comprehensive capital works policy which is sensitive to the realities of the political atmosphere, the physical nature of the piped systems and the historical developments which led to the current situation. Policies must ultimately involve all levels of government, associated interest groups, and the public. With water distribution systems, the main focus must be on improving management at the local level. This chapter will formulate a framework to illustrate the short-comings of the existing situation and develop a rationale to improve it.

From the review in the previous chapters, there emerges three major goals which should ultimately form future water utility policy in Canada, especially as it relates to capital funding:

1) Maintain high levels of service: in order to maintain existing health, economic, and lifestyle standards, the level of service Canadians have grown accustomed to cannot be allowed to diminish in the future; the immediate problems including the current capital works backlog and the reduced public interest in "lifeline" systems must be overcome; demand management can assist in conserving the water resource and preserving the longevity of existing systems already in the ground; long term renovation and replacement plans can assure adequate service levels in the future;

2) Promote greater self-sufficiency among utilities: the reality of the current economic situation, with all levels of government burdened with heavy debt loads, means utilities will have to look less to senior government for capital financing and more toward the users; the undervaluing and continued subsidization of water

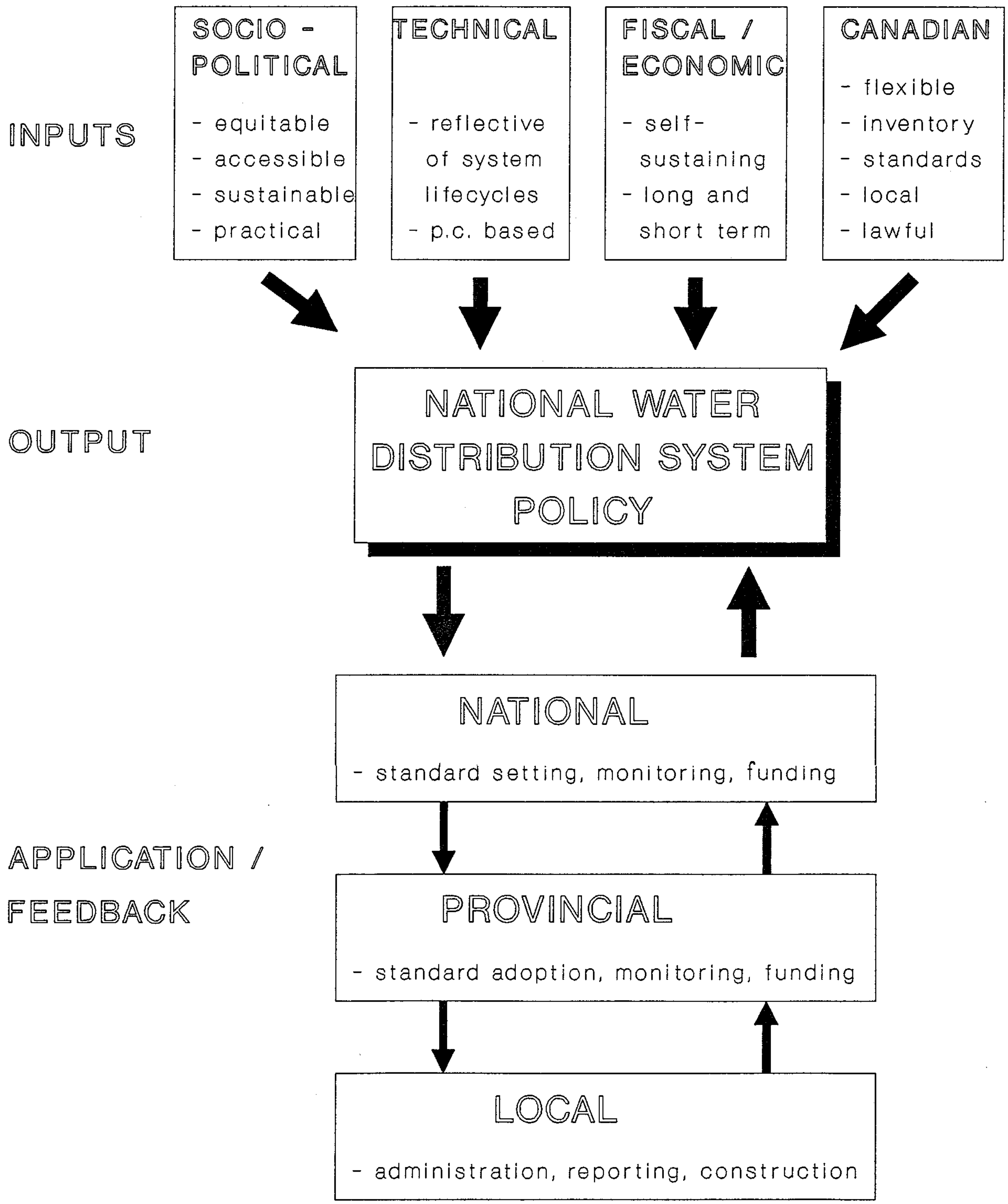
systems will eventually have to stop and the true costs of system upkeep will be passed on through increased water rates both in the short and long terms; the challenge will remain one of maintaining service in an equitable manner both among individual consumers and their communities, recognizing each has different abilities to pay; depreciation of water lines will have to be recognized and system replacement planned for;

3) Promote increased research: research into the implementation of replacement scheduling, decision making, and rehabilitation techniques must be continued; the improvement and application of already developed technologies and models must be promoted especially in the many communities still using inefficient "seat of the pants" techniques to manage the water infrastructure; new construction technologies which are less disruptive and more cost effective must also be further developed to aim at the specific needs which will develop in Canadian communities in the near future;

4) Develop rational service standards and rehabilitation programs: both must be flexible enough to meet the needs and characteristics unique to Canadian communities: condition assessment standards and regional condition monitoring programs need to be rationally developed to both guide communities in their own capital improvement programs as well as protect communities from increased liability; programs and standards must be flexible enough to adapt to communities of varying size, resources, and environments; technical and funding assistance from senior levels of government will still be sought depending largely on the resources available and ability to pay of the respective communities.

As can be seen in Figure 6.1, any national policy aimed at solving the current problems

Figure 6.1: National Water Distribution Policy



with water distribution systems should be based on a number of inputs:

1) Socio-political: equity among users paying for the service must be balanced with the political desire to provide access to good, wholesome water for both individual users, who require a minimal amount of water for good health, and individual communities, many of which must deal with lesser abilities to pay and extreme environmental conditions; policies must also recognize the current sensitivity to environmental impacts and be practical from a cost, standards, and implementation perspective;

2) Technical: policies must be reflective of the physical lifecycle of water systems and incorporate current management technologies developed to manage and rehabilitate water systems; the broad availability of p.c. based data and management systems in even the smallest communities can be taken advantage of;

3) Fiscal / Economic: policies must take into account the current fiscal reality in Canada while trying to improve the funding and revenue generation mechanisms to assure adequate resources will be available to maintain adequate levels of service in Canada in both the long and short terms;

4) Canadian: policies must reflect the inherent environmental, community development, economic, political, health, and constitutional characteristics unique to Canada; programs developed in the U.S. or Europe, while useful as guidelines, will not be directly applicable to the specific problems in this country.

All the above inputs will be incorporated into a national policy which delineates the roles and responsibilities of the national, provincial, and local authorities. Feedback and monitoring of the programs implemented under the policy will be integral to the policy in order to gauge the progress of programs and to improve the policy itself.

This chapter will elaborate further on each of the four main goals and discuss the basic factors for input into a progressive national policy aimed at alleviating the problems of treated water distribution systems in Canada.

6.1. Maintaining high levels of service in Canada

While there is a real short-term rehabilitation backlog due to the pulling back of funding assistance by senior levels of government from areas where traditionally all levels of government once shared, new policies must not only focus on eliminating this crisis but must also address impending long term problems. If current policies are any indication, as a society we seem to be either very naive to the fact that our infrastructure systems are going to eventually wear out or in a state of perpetual denial that problems will ever really develop. The attitudes, roles and involvement of the public, government, and interest groups must be reassessed to optimize use of the current physical systems and assure adequate levels of service in the future.

6.1.1. Eliminating the Current Capital Works Backlog

Much of the publicity over the past decade has focused on the enormous capital improvement backlog which has now developed. This problem has developed over the years due to a combination of policies at all levels of government and thus must be solved in as rational and shared a manner as possible since it did develop out of a shared course of events, decisions, and responsibilities. The short-term solution will ultimately involve increasing expenditures to clear up the backlog. Unfortunately, the sources of funding are by no means assured and up until the recent change in government, no commitment had been made at the federal level. While the FCM recommended a 1/3 1/3 1/3 split among the local, provincial, and federal lines, the previous federal government resisted based largely on reduced spending policies and a rationale that water systems and indeed municipal infrastructure rehabilitation were not part of the federal mandate. There was no precedence for such assistance to an area traditionally considered to be local and provincial domain.

However, insomuch as the federal mandate would be served in such areas as job creation, regional economic development and protection of the national water resource, the federal government could justifiably assume a portion of the required costs. The new Liberal government has recognized this and has announced a program which is a start to solving the problem, but judging by the scale of the commitment, it is by no means the ultimate solution. While the cost to be shared by local government should be significant, any cost-sharing program must recognize that part of today's problem stems from a lack of direction in the past by senior government whose programs of loans and grants rarely encouraged local municipalities to manage or save for eventual replacement. Much like a parent handing out weekly allowances to their children without giving any advice on how to save for a rainy day or on how to properly spend, or how to prepare for the eventuality the allowance would be cut off, the federal and provincial funding programs instilled a perception that senior levels of government would always be there to provide needed capital. Local governments have come to depend and even expect such grants and loans and, intern, undercharge for water service. Although it can be argued that much of the assistance came when times were good and that no one, including the senior levels of government, could have foreseen the cuts adopted over the past years in the name of fiscal responsibility, it is obvious the mounting problems of system deterioration are not wholly a local problem. Any programs aimed at clearing up the current funding shortfalls therefore should involve a level of federal involvement and even more provincial involvement.

Regardless of the commitment or the cost sharing formula, the basic philosophy of any program should be to clean up the mess made by all parties in the past and work toward proper long-term care in the future. In the short term, which may be considered as ranging anywhere from 3 to 10 years, three major problems must be dealt with:

1) Financial Assistance to Municipalities - coming to grips with the financing of the backlog of capital improvements already identified by the FCM and assisting local municipalities in managing financial resources to do so;

2) Improving Information Systems - setting common standards and guidelines for practice by municipalities to better identify required rehabilitation and better estimate the overall scale of the impending problems.

3) Providing Information to Consumers and Managers - information on the current problems and the required solutions must be introduced into the psyche of both users and providers.

6.1.2. Developing Long Term Goals and Plans

Longer-term goals should focus on utilities becoming more self-sustaining through improved long term planning. Consideration must be given to better system management, the setting up of long-term capital replacement funds for both new and existing works, and the overall reduction in consumption and therefor the demand on already taxed systems. National and regional monitoring should be enhanced to allow tracking of trends and the setting of national bench marks for improvements. Education must be continued to allow consumers to realize the benefits and allow for future modifications.

Regardless of the course of action taken, two salient points can be drawn from the reality of physical deterioration of systems over time:

1) Work must eventually be done: capital work to improve existing systems must be done and be continually done in the future, over and above current levels, to clear up the backlog of existing problems and to maintain the existing systems at proper levels of operation within the context of increasing standards and accelerated deterioration;

2) Money must eventually be found: more rational funding policy will be required to properly carry out the additional capital work as existing levels of funding are insufficient to keep ahead of the deterioration, resulting in maintenance operations which are not being effectively utilized.

From the previous discussions, there appears to be five major areas which need to be improved and incorporated into longer range water system management plans:

1) Information: system-wide monitoring of the physical nature and state of repair of individual water distribution networks must be improved; effective information management must be integrated to monitor problems locally and to chart program progress on both a regional and a national level;

2) Standards: policies should maintain minimum national levels of service as they relate to health and economic development; they should recognize that historical local levels of service can vary with respect to non-health related concerns and standards;

3) Funding: policies should incorporate rate structures which balance ability to pay and equity concerns with the concepts of user-pay and demand management; the aim should be at both curbing waste of the water resource and maintaining proper levels of funding for the inevitable future requirements; program cost sharing among all three levels of government should be implemented based upon each level's individual mandate served and their historical role in the development of the individual systems;

4) Education: information on water conservation, actual costs of service, and the current state of repairs associated with these systems is necessary. The "out of sight, out of mind" and "water is cheap" perceptions must be put to rest; policy-makers, consumers, and the public in general must all be aware of the true value of the water resource and the extensive infrastructure required to bring quality water into the home;

5) Research: technical improvements in both new construction and rehabilitation technologies must be sought; management programs should be improved, promoted, and implemented.

Any new policies should recognize that Canadians pay among the lowest water rates in the world, and are second only to the U.S. in per capita water consumption. Over the years, the design community has accommodated this high demand by developing standards which satisfy it. However, with rising construction costs and fewer funds to build, it only makes sense to reduce demand and thereby reduce the system required to meet it. In the long term there could be a down-sizing of some of the standards and an extension of the service life of many existing systems. Demand management would be an invaluable tool to meet this end.

6.1.3 Reacquaint the Public with Lifeline Systems

The real solutions must focus on the real problems. The real problem with water distribution systems is not characterized by rapidly collapsing structures, nor one of immediate and widespread risks to health, nor one of fraudulent neglect. Rather, the problem emanates out of many incremental decisions, physical processes, and changes in standards and attitudes over the years. The problem is one of slow decay versus imminent catastrophe. Public and political attitudes have shifted priorities and funding away from basic infrastructure needs.

Accurate recognition of the need to rehabilitate a water system by a utility does not necessarily guarantee the work will be carried out. The current funding shortfalls are not only due to increases in the need to rehabilitate, but political and public concern which does not match this increasing need to rehabilitate the systems. As Grigg (1988, p. 62) notes, the natural force in the political marketplace is to defer capital needs. As in most publicly controlled utilities, the criteria for making decisions about when to carry out capital works used by the operational side of a utility do not necessarily match those of the funding side.

Utilities should raise the awareness of the true value of such "lifeline" systems and the need to at least maintain existing service levels. When water distribution systems were first developed, the users were aware of the huge benefits and were willing to allocate significant resources to develop them. However, today we have become so accustomed to the presence of these systems, which have been maintained without a great deal of expense, that it is very distasteful to think a water bill should ever have to increase by two or three fold. The realization of the true benefits and the real costs have been lost over time.

Introducing information to consumers and system managers on the current problems and the required solutions must be carried out through multi-media education programs. On water bills and in the media, issues must be raised including the nature of the capital works backlog, the undervaluing of water, and the need for conservation, especially within the current public context where ecosystem impacts and sustainable development issues are forcing us to rethink our past habits, especially as they apply to growth and new development. To mobilize support for such programs, both the politicians and the voters must recognize the facts of the issue.

Competition among public programs for funding and the general trend away from increased levels of spending means future funding levels from higher levels of government will not increase drastically, though there an indication they will increase marginally. To better assure that there is going to be some increase, utilities in all communities, and especially the small ones, should consider improvements to system management which allow better identification and more effective mitigation of system deficiencies. The adoption of such techniques at the local level can increase the confidence of higher levels of government concerned that any moneys made available will be spent properly. Better management will also instill confidence in the users that systems are being operated in the most effective manner and any users fees are being spent wisely.

One fact which must be realized in any policy discussion must be the underlying reason we have such extensive water distribution systems in Canadian communities. These systems did not merely develop out of a need to increase our everyday comfort and convenience or our standard of living, nor was their initial development necessarily spawned from public health concerns. Although these were indirectly satisfied, the early development of water systems, as well as much of our existing infrastructure, was spawned out of economic concerns, particularly protection from fire. The development of the physical infrastructure produced employment and contributed to the prosperity of the nation. The importance of this cannot be diminished as any investment in water distribution systems is an investment in the economic fabric of Canada. Frequently this is overlooked and, as gauged by public opinion, and recent media coverage, is often lost in the discussions.

6.1.4 Reassessing the Major Roles

When identifying the problems associated with water distribution infrastructure, it is not difficult to implicate nearly all levels of the political spectrum, not to mention the design, planning, and educational communities. Rather than lay blame for the problems of the past, it is going to become more and more evident that perhaps the roles of each must be rethought. Any national policy development should consider matching specific tasks and responsibilities to appropriate bodies; Table 6.1 outlines the potential roles of agencies currently involved with the provision of water infrastructure.

Table 6.1: Roles and Organization

---------------------- Supply Management ----------------------

Area	Sub-Area	Major Role	Secondary Role
Information Gathering/ Condition Monitoring Systems	Standards and Guidelines	Provincial	National
	Overall Monitoring of Systems	Provincial	National
	Information System Development	Provincial	National/Local
	Assessment of Existing Packages	Provincial	Local
	Implementation of Information System	Provincial	Local
	Training and Technical Support	Provincial	-
	Feedback	Provincial	Local/National
	Information Uploading - Regional	Provincial	-
	Information Gathering - Regional	Provincial	-
	System Monitoring - Local	Local	-
	Information Uploading - Local	Local	-
	Information Gathering - Local	Local	-
Rehabilitation/Replacement Models for Decision Making	Standard Setting:		
	- National: ie. health, economic dev.	National	-
	- Prov: ie. construction, design	Provincial	-
	Assessment of Inputs:		
	- System Condition Data	Provincial	Local
	- Construction Techniques and Costs	Provincial	Local
	Prioritizing of Needs	Provincial	-
	Model Development	Provincial	National/Local
	Feedback	Provincial	Local/National
	Model Implementation	Local	Provincial
Provision of Capital	Major Upgrades to National Standard	National	Provincial/Local
	Major Upgrades to Provincial Standard	Provincial	Local
	Long Term Capital Replacement	Local	Prov./National
	Minor/Normal Upgrades	Local	-

---------------------- Demand Management ----------------------

Area	Sub-Area	Major Role	Secondary Role
Rate Structure Setting	Guidelines and Standards	Provincial	National
	Cost Analysis (O&M, replacement)	Local	Provincial
	Rate Setting	Local	Provincial
Conservation	Public Awareness	Provincial	Local/National
	Incentive Guidelines	Provincial	-
	Implementation with Incentives	Local	Provincial
Education Provincial/Local	Conservation	National	Provincial
	True Cost of Water and Systems	Provincial	National/Local
	User Pay with Equity Concerns	Provincial	National/Local

As can be expected, all encompassing tasks such as standard setting and overall program monitoring should be carried out at the national and provincial levels, with raw data collected locally via individual system monitoring. Program implementation, though it may be coordinated at the provincial level, should be carried out locally by operations staff familiar with the water systems.

Senior levels of government can provide funds and technical assistance in the areas associated with overall national interests. Small utilities which have neither the resources not the technical ability to develop and implement independent programs on their own could benefit most from technical agencies within the government or from funding to allow consultants to develop programs at the local level. Provincial and federal governments should play a leading role in developing standards and guidelines critical to the standardization of any programs. Senior governments can also help through seed money or administrative assistance in the pursuit of innovative funding mechanisms. Still, any financing from senior government should be conditional upon the applicants completing an overall system assessment and a general plan for managing the systems in the future.

Involvement need not be limited to government agencies but should include professional and technical bodies such as the AWWA, the Western Canada Water and Wastewater Association, or special interest groups such as the FCM or FACE as outlined in Table 6.2.

Regardless of the organizational input into any national policies, the aim of all organizations should be to optimize the use of the existing pipes in the ground. While structural techniques can increase the useful life of pipes, non-structural demand management techniques can effectively involve the individual consumer to reduce demand and thereby postpone or even eliminate the need for major capital expansions. In doing so, the usefulness of system components are maintained, eliminating the need to abandon components that had not reached the end of their physical lifecycle.

Table 6.2: Examples of organizational input and involvement at various levels

Type	Local	Provincial/Regional	National
Government	Municipal: - council - waterworks staff	Provincial: - Dept. of Environment - Dept. of Health - Dept. of Municipal Affairs - Dept. of Public Works - Funding/Grant Agencies	Federal: - Dept. of Environment - Dept. of Health/Welfare - CMHC, PFRA
Public	Local surveys/meetings	Workshops/meetings	Workshops/meetings
Interest Groups	Chamber of Commerce Universities	AWWA affiliates UDI affiliates	FCM, FACE CSA

Demand management can also increase consumer awareness of the true value of the water resource through conservation-based advertising and through more representative water pricing schemes. Reduced flows will soften the impact and occurrence of crisis type situations, and reduce the dependence on crisis type management in the water supply field. Reduced demand can also result in lower operational pressures and reduced breakage occurrences.

6.2. Improved Replacement and Decision Guidelines

While increasing the levels of spending on water distribution, and indeed all infrastructure systems, will ultimately solve problems, the effectiveness of any spending program will depend largely on the effectiveness of the decision making tools and problem identification methods adopted. Within water distribution system management, the development, implementation, and standardization of such decision making tools is sadly lacking.

From the literature it is evident that there are two basic shortcomings of the current "seat of the pants" approaches:

1) Non-representative of the physical systems: utilities have not necessarily adopted pipe management techniques which reflect the characteristics of the pipe's lifecycle; in order to maintain credibility and assist in the competition for scarcer funds, rational approaches to "what to fix when" must be based on an evaluation of accepted performance, structural, and external factors which can accurately characterize the condition of a pipe; in addition, the real consequences and risks associated with inaction must be demonstrated to the decision makers.

2) Inadequate allocation of resources to meet the identified rehabilitation demand: once a component is rationally designated for rehabilitation, there must be sufficient funds in place to allow the required work; currently due to reduced public and political interest, much of the work which must be done is not being done, with the public resources being directed elsewhere.

Under ideal conditions, a water distribution system would involve an ideal system serving an ideal consumer in a ideal world. The system would be constructed with ideal information about the users and the expected loads and conditions; it would be operated and maintained in the most economically and socially acceptable manner, supplying water of the highest quality to consumers who use it only in optimum amounts. Of course, even in an ideal world, the system would wear out, but would be rehabilitated or replaced in the optimum fashion at the optimum time. Unfortunately we do not live in a perfect world, so less than optimal circumstances always exist.

Marks (1987) identifies six approaches commonly adopted by utilities in effecting capital replacement decisions:

1) minimalistic: "if it ain't broke, don't fix it"
2) crisis management: "fix the worst first"
3) opportunistic scheduling: "if someone else will pay, fix it"
4) condition monitoring: using pre-specified maintenance standards
5) risk management: repair facilities at risk
6) preventative maintenance: cradle to grave concern for maintenance.

In communities today, the first three strategies are the most prevalent, though they are the least effective. The last three strategies, while more effective, are generally limited to larger municipalities which have the substantial management resources required to develop and implement such management techniques. That is not to say most communities have not necessarily made a conscious decision to adopt less than adequate strategies, but, as is often the case, they have not because of resource constraints or because of relatively minor problems to date. However, in order to maintain public confidence in the management of such systems, it is prudent that communities adopt improved techniques especially considering the inevitable fact that the systems will wear out and that help from senior levels of government may not always be readily forthcoming.

Much of the current problem in infrastructure financing can best be characterized as a distancing between the needs of the operational side identified at the local public works level and the reality of the resources allocated by the funding side as represented by the political process. The operational side's mandate is to provide the user with the best possible service from the best possible system, while the funding side has to factor in a fiscal limit set by public and political bodies. This limit is directly related to the importance of the services provided relative to the other services provided by the community. When the reality is as it is today, where water supply is rarely at the top of the public priorities list, there will always be a discrepancy between the operational needs and the financial resources made available.

In this age of competition among programs, the operational side has to strengthen its case and raise the profile of the needs in water supply. The criteria used by the operational side and the funding side must not only be brought closer together, but at the same time must be improved to assure optimum rehabilitation decisions. A number of options already discussed can be at the individual utility's disposal to affect the decision making process.

A utility can improve its management image by focusing on the improvement of long-term rehabilitation plans rather than just short-term patching, and by attempting to minimize the impacts and costs of maintaining such long-term plans. New technologies such as trenchless technologies can help to alleviate the negative image of water system repair, which is often one of large scale disruption and inconvenience. The ultimate goal of future programs would be to assure that at all times adequate levels of service are maintained.

All too often, the only time level of service becomes an issue is "after the fact" following a major crisis. Unfortunately, the wrong time to discuss effective management is following a catastrophic fire or an earthquake, though it is often the most common. There needs to be a change in attitudes regarding water systems away from the perception they are merely pipes in the ground toward one which recognizes their true importance as "lifelines".

The increase in information can be accompanied by public promotion to raise the profile of water utilities and promote awareness through direct educational involvement. Both the costs and the benefits of large scale programs must be delineated. The setting and adoption of service level standards can be enhanced by public awareness and direct public involvement.

Together, the options outlined can help to bring the funding agency criteria and the operational criteria closer together, and closer to a rational optimum. When analyzing the long-term management needs of water distribution systems, mechanisms must be put in place to track three important criteria:

1) the current state of the existing systems from both a physical and a funding perspective;

2) the optimum replacement and/or rehabilitation schedule on local and regional levels;

3) the required need defined as the difference between the current state and the optimum.

The current state includes the specifics related to the physical properties of the systems, including pipe sizes, material types, and age, the environmental concerns specific to installations within Canada, such as soil types, frost concerns, and properties of the water carried, and finally the political and social environment related to funding and the prominence of such systems in the social psyche.

Effective system management techniques which recognize the inherent nature of a water distribution systems life cycle have been developed but now need to be publicly adopted on a large scale over communities of varying sizes, needs, and levels of sophistication. The development and wide-spread implementation of such programs will not occur overnight. For example, while the development of pavement management systems (PMS) started in the late 1960s and were quite well developed by the mid 1970s (Hudson and Haas 1976), many municipalities have just begun to implement them. Still, the implementation of computer based information and decision systems for water systems can be accelerated due to the presence of existing models such as PMS, and due to the rapid advances in personal computer software regarding database management, graphics programs, and geographic information systems (GIS). Today, most of even the smallest communities have personal computer capabilities for at least administrative purposes.

Currently such optimization techniques are being used successfully only in a few of the largest utilities. Real innovation can come from widespread implementation of some of these methods rather than through the development of new techniques which essentially re-invent the wheel. As Grigg (1988) points out, "the challenge in public works is mostly making the best use of what is available, rather than developing new approaches that are not already available to business and industry".

Once the current state and the optimum requirements are identified, the system needs can be calculated and resource allocation planned. Comprehensive programs which involve the monitoring and feedback both at local and regional levels must be developed such that the unique resources available at each level are best utilized. While research into technologies which minimize the costs and negative impacts of construction and rehabilitation needs to be promoted, appropriate technologies must be matched to highly variable and typically unique rehabilitation circumstances which can vary greatly depending on the size, geography, public attitudes and perceptions, and monetary resources of any particular community.

6.2.1. Determining when to replace a pipe

Utility managers are responsible for managing the built systems within the organizational and fiscal constraints as set out by the governing body. As Grigg (1988, p. 264) points out, any solutions to the current infrastructure management problems will be multi-disciplinary and multi-faceted involving organizational management of the organization, project management of the projects, and operational management of the built systems.

In all facets of the management of a water distribution system, there must be an implicit understanding of the nature of such systems. Systems are characterized by incremental development over the years with different people, contractors, agencies, and standards involved in each stage of the development. With such a mode of development, gaps, inaccuracies, and imperfections in the information will develop. In addition, each individual component added to a system has a unique lifecycle which, combined with all the other components, contributes to the aggregate lifecycle of the overall system. Unfortunately, due to the incremental development of continuous systems such as water distribution networks, identification of overall system lifecycles is not easy. Still, within a water system or any individual component, there are three major phases which characterize the lifecycle:

1) Phase I: planning, design, construction, and start-up,

2) Phase II: normal operation and maintenance,

3) Phase III: wear-out, rehabilitation, and replacement.

A basic recognition of these three phases is essential to determining the optimum time and sequence to replace such systems. Unfortunately, professional technical and engineering education programs tend to focus heavily on the initial design phase, with little effort directed at how to properly operate and maintain such systems for long life and even less effort at rationalizing the overall lifecycle.

The planning, design, and construction technologies associated with phase I are well entrenched and typically well funded in Canada. In the planning stages, empirical relations based on historical trends in demand are applied to population and economic forecasts to estimate anticipated demands. These demands are then used to calculated system requirements given a set of performance criteria or "standards." For a water distribution system, typical performance criteria may entail maintaining a residual pressure at the curb of 45 m of head under maximum daily demand, or maintaining 30 m of head under maximum hour demand or maximum daily demand plus fire flows (Adams and Heinke 1987). A hydraulic analysis then determines pipe sizes and pumping and storage requirements. Once these components are sized, they are designed to satisfy structural standards given the anticipated set of environmental loads. Structural design standards for the pipes are typically set by the Canadian Standards Association or a similar body (AWWA, NSF, CGSB), while structural standards for facilities are designed to meet various national, regional, and/or local building, electrical, and structural codes. Construction entails a number of uncertainties, ranging from quality control, to techniques and materials incorporated, to environmental conditions encountered. In many cases, the quality of construction is the overriding factor which determines the proper functioning and continued life of a system.

Phase II follows the construction and breaking-in of a new system, and includes general maintenance and normal operation. According to the FCM, attention to these operations is not an issue as it has remained at an adequate level over the past 20 years. Components are inspected, breaks are repaired, faulty components are repaired, etc.

Phase III involves the wear-out of the system and is typically the most overlooked phase in a water distribution systems life. Proper identification and management procedures at this phase are significant not only because they assure the proper functioning of existing systems, but they can provide valuable information and technologies which can refine both the design and maintenance phases.

Both Phase I and Phase III are similar in that they often involve large capital expenditures over short periods of time and as such require more time and site specific planning inputs than the maintenance phase. However, Adams and Heinke (1987) note there are important characteristics which do distinguish the two phases: Phase I involves the application of deterministic standards or criteria to uncertain conditions, while Phase III involves the application of probabilistic standards or criteria to certain conditions. This distinction is based on the premise that in developing a new system, uncertainty exists about actual system growth or environmental conditions, but once a system is initiated and operated, the actual loads and demands are realized. Unfortunately, without a program to monitor or provide feedback, the benefit of increased certainty following phase I can be lost.

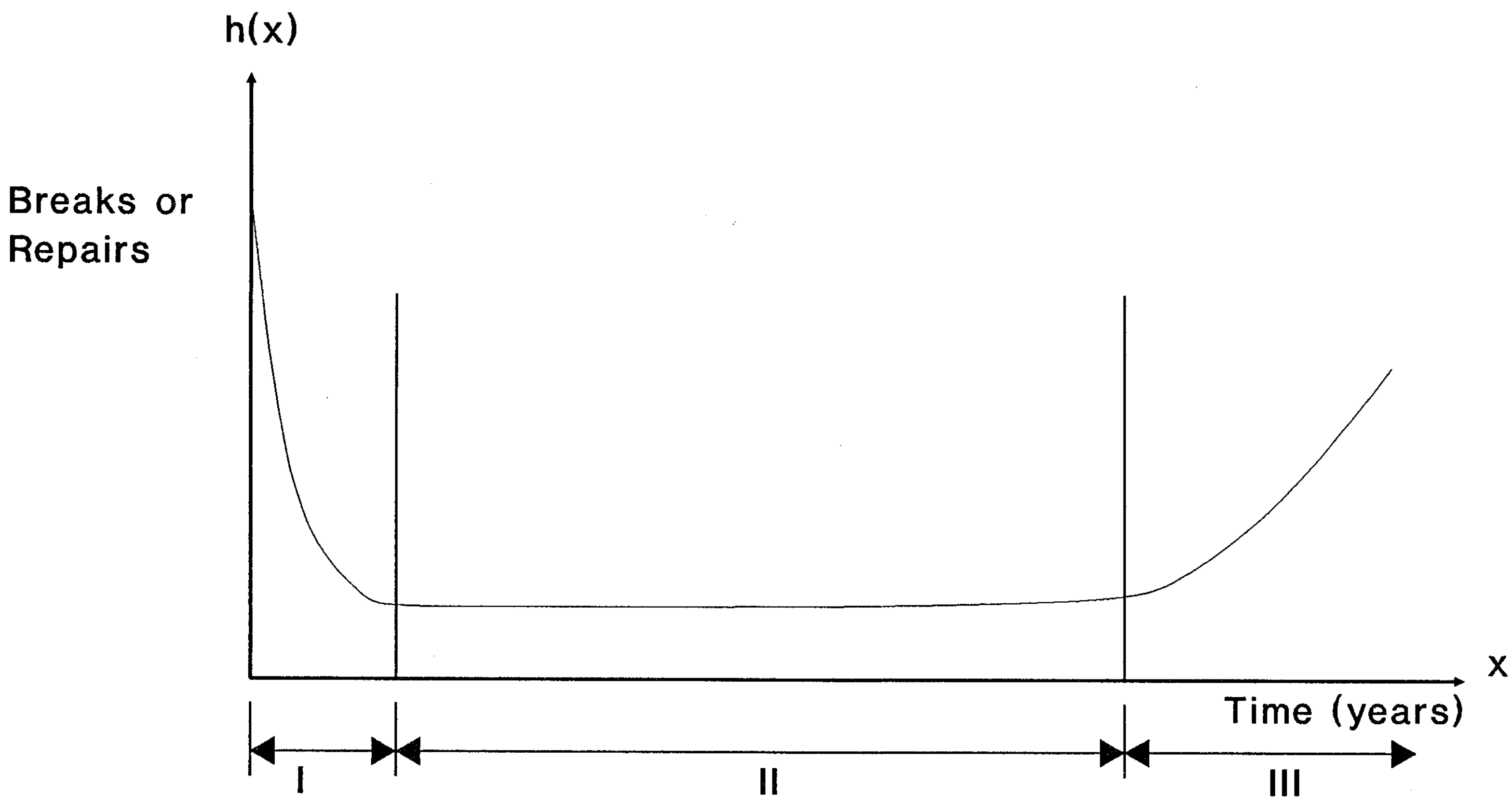
Monitoring is an important management component in all three phases and is the only means of accurately distinguishing between the phases. For instance, the boundary between the maintenance and rehabilitation phases can be somewhat arbitrary, based largely on predetermined scales of work or budgetary limits. Monitoring can also be important in the setting of overall design standards for future new works, and to the operation of effective maintenance programs, but undoubtedly the one area where it is critical is in the setting of effective rehabilitation criteria and the effective allocation of rehabilitation resources.

A broad base of inputs and criteria (ie. economics, service, reduced frequency of crises) can be included to standardize when a pipe moves from phase II into phase III and what action is specifically required to improve the pipe. Regardless of the inputs, in order to determine when a water distribution system or any one of its components demands attention, three basic factors should typically be monitored:

1) Structural Adequacy of the system,
2) Performance Adequacy of the system,
3) External Factors.

The "structural adequacy" of a system relates to the actual pipe being able to maintain its physical integrity, and is often measured in terms of high breakage rates or leaks and is realized in terms of high maintenance costs. The nature of the structural adequacy is best illustrated by the "bath-tub" type hazard function discussed Andreou and Marks (1987). As can be seen, this function closely resembles the overall lifecycle of a piped system, a lifecycle very much determined by structural considerations. Water pipes when initially installed often have a high repair event for the initial years when in the break-in stage (see Figure 6.2). This is followed by a long period of regular maintenance where none or one or two breaks may be experienced by the pipe. Eventually, the pipe deteriorates to a point where it enters the "wear-out" stage or the "fast-break" stage which Marks (1987) notes occurs after about 40 years and is typically signalled by two

Figure 6.2: Water main structural lifecycle



I - Start-Up Phase (normally 1 to 3 years)

II - Normal Operation Phase

III - Wear-Out Phase

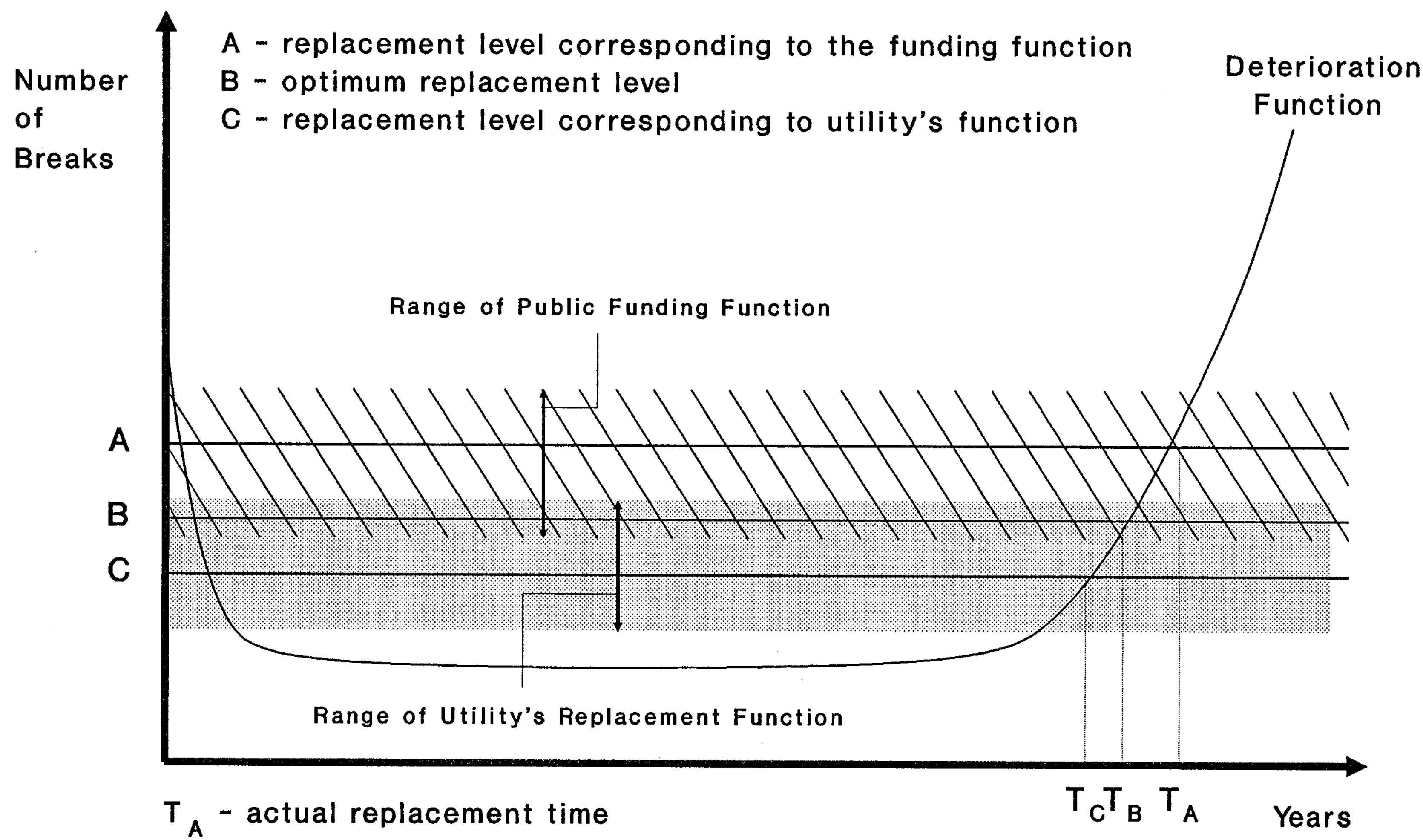
breaks occurring in relatively rapid succession. In this stage, the break rate no longer is related to the age of the pipe, but becomes relatively constant.

When determining the optimum replacement time for a pipe, ideally one would be able to locate the condition of the pipe on the hazard curve and through an economic analysis similar to the one presented by Shamir and Howard (1979) determine the optimum replacement time. Unfortunately, common "seat of the pants" techniques overshoot or undershoot this optimum. Further, since the point at which a pipe enters the fast breaking stage varies with pipe material and conditions, replacement schemes based simply on age or maximum breakage rate criteria can result in premature replacement, which represents an under-utilization through loss of potential use, or late replacement which results in a loss of maintenance resources. The combination of less than optimum replacement scheduling combined with public funding which does not necessarily correspond with the utilities identified needs can result in less than optimum replacement timing (see Figure 6.3).

"Performance criteria" are typically represented by system pressure for the given system demand, typically measured as flow (Adams and Henke 1987). Over the life of a pipe, deterioration due to tuberculation can reduce the effective diameter of a pipe and increase the roughness. Often these effects are combined into an equivalent reduced Hazen-Williams "C" value.

The basis and extent for measuring performance criteria must be unambiguous to avoid ineffective or inefficient actions being taken. For instance, the criteria may be based on providing a minimum service pressure on a peak hour with a high degree of reliability over the entire system, in which case the measurement should probably be taken at the far reaches of the system or points where pressure is known to be poor.

Figure 6.3: Water main replacement scheduling



T_A - actual replacement time

T_B - optimum replacement time

T_C - utilities calculated optimum replacement time

Similarly, the criteria may be to provide fire flow on a peak day or to maintain a minimum average pressure over the entire system, realizing that the distributional aspects must be recognized so that the average is not made up of extreme highs and lows. In any case, such performance criteria must adequately reflect the true nature of the communities level of service expectations.

Probably the least predictable and most difficult to systematize are the "external factors", or the system criteria external to the actual physical performance and operation of the pipe. External factors are often one-time events and are characteristically unpredictable; they can influence decisions to such an extent that they completely overshadow any structural or performance concerns and as such they can include:

1) increased public concern over pipe materials related to health and water quality reflected in increased water quality standards,
2) increased availability of cheap rehabilitation money,
3) increase in standards related to safety (fire flows),
4) increased concern regarding liability due to fire and flood damage,
5) increased demand above anticipated design capacity due to unforeseen growth,
6) increased political involvement in the decision making process,
7) increased need to replace based on coordination with other programs (ie. surface improvements, etc.),
8) increased legislation or regulation.

Due to the unpredictable nature of the such external factors, water utilities tend to base capital plans on the more easily measured structural and performance criteria. External factors are also difficult to quantify and must be expressed in some type of qualitative index to be included in any analysis. Still, because of the longevity of water systems, external factors are often the over-riding factors influencing decisions to rehabilitate.

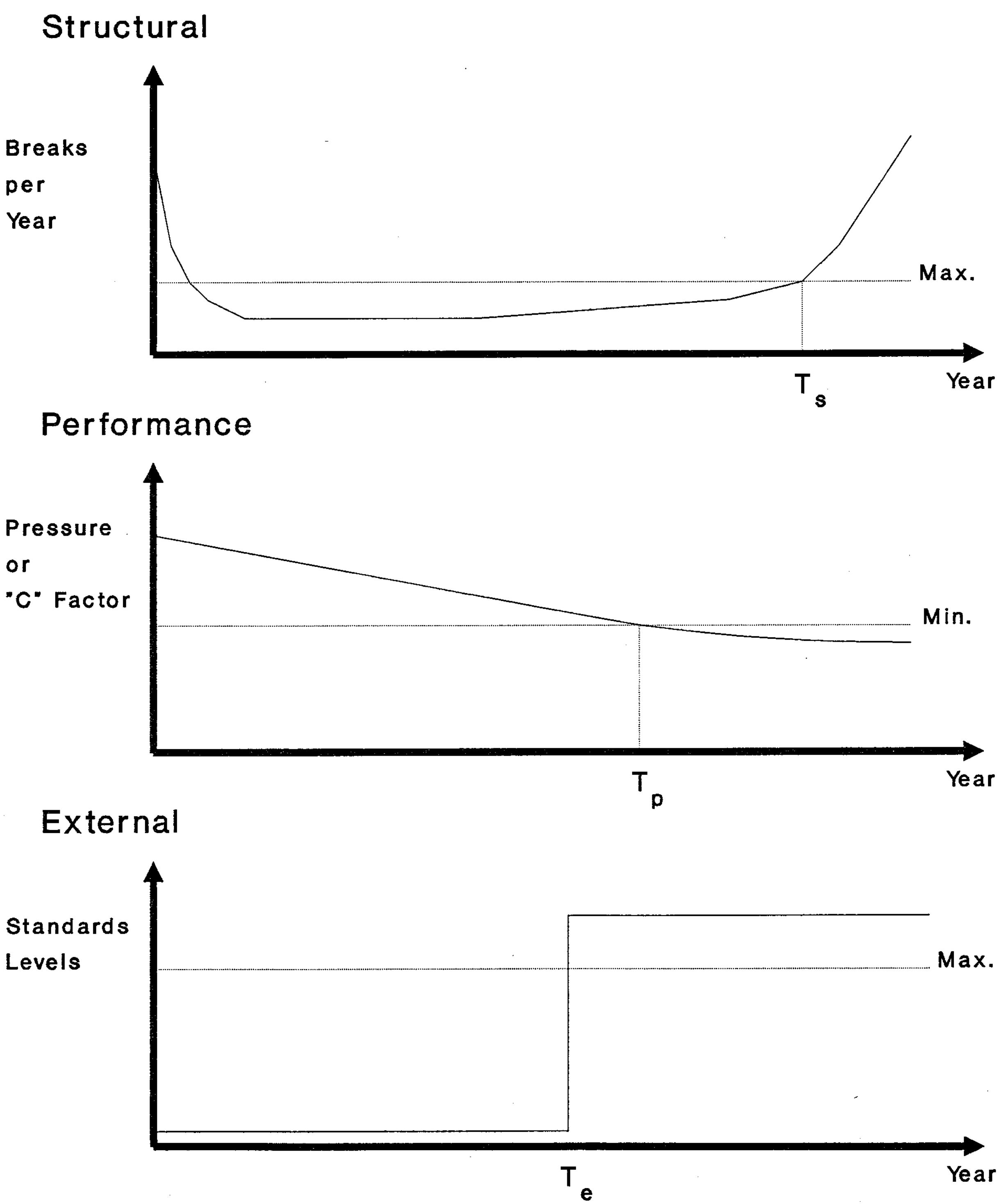
As mentioned, any one of the three criteria can be the primary influence in the need to rehabilitate or two or all three may combine to promote the need to rehabilitate as can be seen in Figure 6.4. Policies should be developed which promote the development of standardized structural and performance criteria, and assist in identifying trends related to external factors which could influence rehabilitation decisions. External factors, since they typically emanate outside the normal operational realm of the utility, will best be tracked through better communication between the utility and outside agencies responsible for planning, funding, public health, and insurance for instance.

6.2.2. Condition Assessment and Monitoring

As discussed, as current comprehensive information is sadly lacking, infrastructure rehabilitation policies should first focus on identification of the extent and nature of the current problem prior to generating any large scale mitigative solutions.

O'Day (1983) acknowledges that resistance to spending money on information and management systems can be expected, especially when money is scarce, but argues that such systems will allow scarce resources to be stretched even further. In the private sector, financial consultants, investment brokers, and management professionals are valuable primarily because they help in deciding where and when to invest limited resources in order to maximize the desired benefits. The decisions are invariably based on systems which effectively gather and assimilate the best, rather than the most, information. The value of such information systems can be potentially just as great to local government.

Figure 6.4: Criteria involved in a rehabilitation decision



These information systems should not remain pure data gathering systems which are designed for the sole purpose of supplying statistics, but should be full fledged information systems which are readily useable and accessible to the decision making processes regarding all facets of system management, including planning, design, construction, maintenance, and rehabilitation.

One area which these systems would prove invaluable is in the area of funding allocation, especially for grant programs aimed at improving water distribution system condition. Condition assessments of existing water distribution systems would be a pre-requisite for funding and could include a review of the following in any particular community:

1) leakage survey,
2) identify repairs for deficiencies (not day to day maintenance),
3) identify procedures to extend system life (ie. cleaning and lining),
4) identify replacement requirements,
5) review the current rate structure and development policies for potential future financing options (ie. user charges, development cost charges, etc.)

6.2.3. Development of National Standards

Maintenance and condition monitoring criteria must be standardized and implemented nationally to assure comparable system conditions throughout all utilities. Broad and flexible condition assessment criteria must be developed to allow assessment, application, modification, and implementation among greatly varying communities at the local level.

As illustrated in Table 6.1, programs must ultimately be carried out at the local level, but senior levels of government or national groups such as the FCM or the AWWA should coordinate and manage the standard setting and monitoring program over the entire country. National bodies would be instrumental in identifying communities with similar problems and networking such communities to assist each other sharing common experiences.

Such information and decision making systems should aim at standardizing system condition criteria to allow a more accurate assessment of system needs and to allow ease of gathering and comparison among different utilities. Previous large scale regional surveys (FCM 1984, McIntyre and Elstad 1987) have only been able to collect system condition information based on local criteria, which can be quite subjective, being based on the managers perceptions rather than actual predetermined standardized criteria. This adds a great degree of uncertainty to national or regional estimates of cost and condition as some communities may choose to adopt very high standards and would therefore estimate system condition to be much lower than average and the resources required much higher.

National rehabilitation standards for water distribution systems are currently being investigated by the FCM (Curtis 1991a) and will provide a point of reference which can be debated publicly and politically, and eventually adopted to help standardize the criteria for determining system condition. Through the development, debate, and adoption process, the increased profile of the levels of service in Canada may help to educate both system users and managers on the issues and crystallize their positions on desired levels of service.

More information on breakage rates, leakage rates, and repair costs for the various sized communities would be helpful in such analyses as this information is lacking right now. Long term monitoring of the newer pipe materials now being installed such as polyethylene and p.v.c. would also be beneficial.

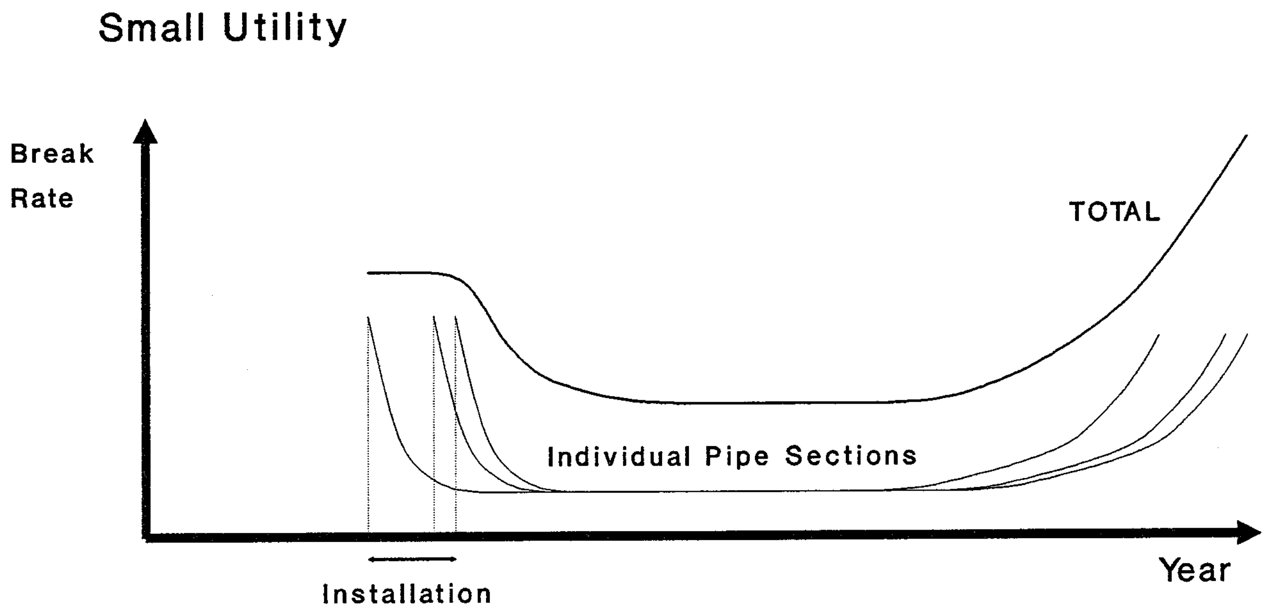
Technical research into improved construction techniques is also needed, particularly trenchless techniques which concentrate on the small diameter cast iron and ductile iron mains which will be the prevalent materials requiring replacement in Canadian town and cities. Application of trenchless technologies to water mains, with frequent obstacles such as valves and services, will be a major challenge.

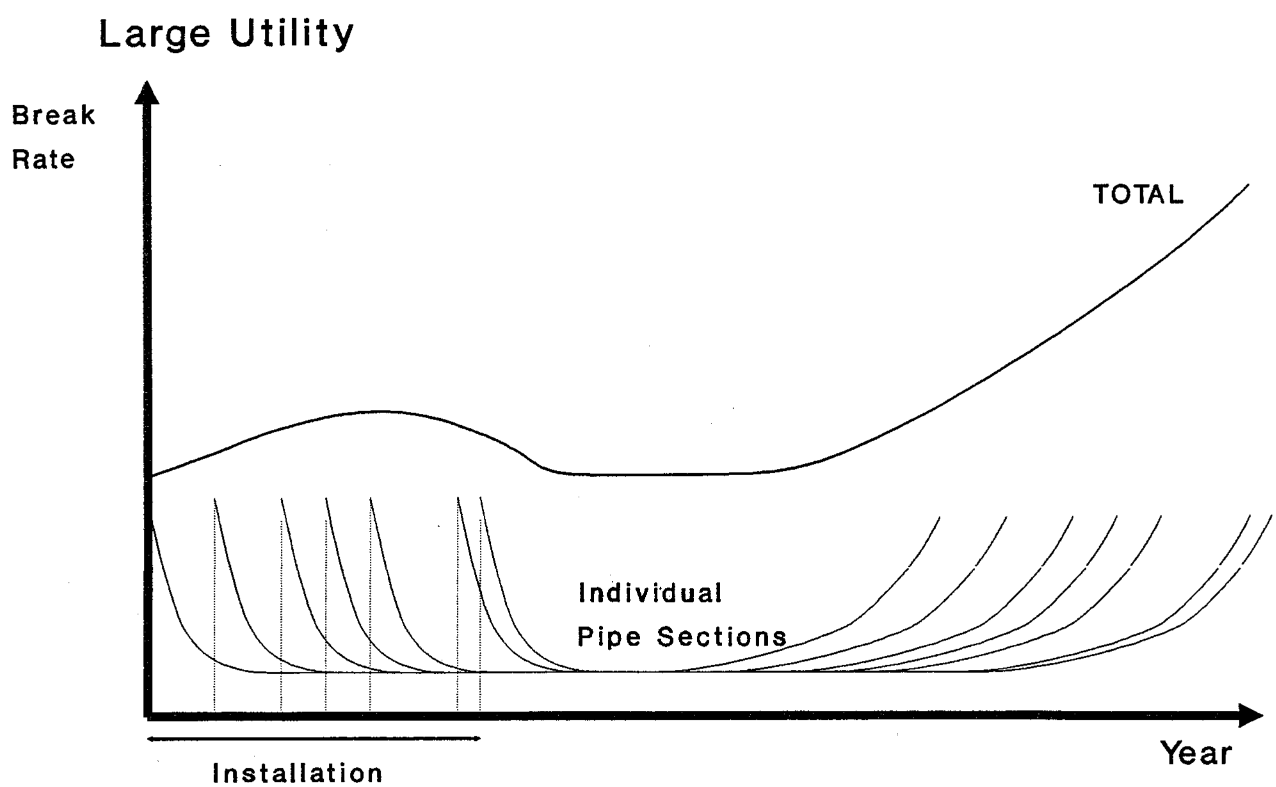
6.2.4. Varying Communities

As reviewed in earlier chapters, Canadian water distribution systems include a varied mix of material, pipe sizes, age, and physical conditions. The systems are geographically and physically isolated from one another though each has one major purpose, to effectively deliver water of good quality at adequate flows and pressures. While new materials and construction techniques over the years may have reduced the initial costs of construction and allowed for the extensive development of water systems in even the smallest of communities, some of the newer materials and techniques have resulted in reduced pipe life. System deterioration is therefore a small town problem just as much as it is a big city problem.

No one management policy will be entirely appropriate for all communities nor all systems. System rehabilitation "needs curves" will vary among utilities and even vary within a utility among the individual pipes. Figure 6.5 illustrates the difference which can exist between the structural needs curves of a small and a large utility. In a typical small Canadian community for example, assuming most the of the water distribution system was installed over a ten year period between 1950 and 1960, the environment and

Figure 6.5: Conceptual model of overall system break rates





construction can be expected to be relatively constant over the town. Assuming there has been relatively slow growth since installation, the structural deterioration will not be a major problem for the initial 30 to 40 years after installation, but can be expected to increase relatively rapidly after that given the general hazard function. The small community will require a relatively large investment in a relatively short period of time to replace the deteriorated system.

In larger communities where the distribution system has been installed in a more incremental fashion, the problems associated with structural deterioration will be more constant over time, making the task of dealing with it somewhat easier since resource and labor levels can also be maintained at a more constant level. In most large Canadian cities therefore, information and management systems are well developed, though the techniques used to determine rehabilitation needs still vary widely. In many smaller Canadian communities, not only have the rehabilitation needs not been investigated in detail, but even the most basic system information, such as pipe sizes or system length, are not available or in a useful format to facilitate even the most simple analysis.

6.2.5. Program Strategies for Various Sizes of Communities

The size of the community will typically dictate the level of sophistication of any rehabilitation program and the resources available to implement it. In Canada the 31 largest communities contain the least amount of pipe per capita, have the lowest domestic consumption rates, and serve the largest percentage of the population. Efforts to reduce leaks and breaks and subsequently the costs associated with repair and lost water will be very effective here where systems are concentrated and therefore more manageable to assess on a systematic basis. Since the largest volumes of water flow here, it is reasonable to assume the largest volume of lost water can be found. In addition, with the large centres growing at increasing rates, work on reducing the problems within today's existing distribution systems will reduce future problems which could arise as larger populations connect.

The 272 medium sized communities in Canada use a volume of water for domestic use which is almost equal to that of the larger communities, but at a domestic per capita rate which is 38 percent higher than in the larger centres. Undoubtedly, some of this could be accounted for by the relatively large number of traditional single family residences which have significant lawn watering requirements. Still, water conservation measures in these communities could reduce the consumption rate and the overall water consumption significantly. Programs aimed at reducing leakage and breaks would also be effective here as total flows are high, though the program would have to be spread out to nearly ten times the number of communities as the larger centres, thereby increasing administration costs. Recent growth trends in such communities signify a growth rate which is stabilizing.

In the smallest centres, conservation methods may be an effective means of reducing the very high per capita domestic consumption rates. Programs aimed at reducing breaks and leaks could be very effective on a per capita basis as these communities contain the largest amount of mains per capita, thus breakage and leakage rates could be high per capita. However, the administrative and training costs associated with implementing such a program in nearly 2,600 communities could be high. In addition, with staff size very small, there may not be the resources in each community to manage such a program on a day to day basis. Thus, it may be easier to have small communities gather the data and monitor the day to day activities, but have each submit reports to a larger agency, perhaps a provincial government department or a regional planning board, which would then be responsible for synthesizing longer range plans and analyses. With growth rates in many of these small communities decreasing, it is likely the tax base will not be growing substantially. Thus the emphasis in these communities should be on getting the most out of existing systems rather than planning for major future expansions. Land uses should be assessed to assure an optimum number of people are being served by existing system. Large areas of undeveloped lands or vacant lots adjacent to existing pipes should be promoted for development versus areas outside or on the fringe of existing services. While total water volume savings may not be significant in small communities which only account for 17 percent of national domestic water flows, on a per capita basis these communities represent the greatest potential for improvements. From a piping perspective, the systems in these small communities were installed in the last 30 to 40 years using new materials that have proven to be less durable than older pipes. Thus, the problems of system deterioration in these communities can not be discounted as they will not be far behind that of the larger older systems of larger centres.

6.3. Long Term Fiscal Policy Restructuring

While elaborate condition assessment programs and pipe deterioration models may easily identify a pipe as physically in need of major renovation or replacement, there has not yet been a program developed which guarantees that the funds will be appropriated to actually carry out the work. While the physical processes of corrosion and fatigue are complex, the complexity of these physical processes pale by comparison to the decision making processes which determine whether the will, determination, and most importantly the financial resources will be available to carry out the needed work. Because water systems are so extensive, it can be expected that the costs of any new programs will be great, and as such the speed at which decisions will be made to spend money will undoubtedly be very slow. Still, in relative terms the cost of solving the problems are not excessive nor prohibitive. Increasing water rates to levels not uncommon in Europe would greatly assist in solving many of the problems. While such change may involve a slow and arduous process of informing consumers of the true cost of water service and the need to phase out unnecessary subsidization, the end result will be a more enlightened consumer and more effective and efficient water systems.

At the root of any new national public utility management strategies must be more rational fiscal policies. Such policies must be far reaching and based on a philosophy which includes three major ingredients:

1) <u>Implementing more cost-effective and value-reflective programs</u>: cost-effective information management systems which optimize overall maintenance and rehabilitation dollars as well as realistic water rate structures which reflect the true value and costs of water systems must be adopted; a recognition of the long-range capital replacement needs should now be an integral part of all local programs;

2) <u>Opening the books</u>: the cost-effective and value-reflective programs must be preceded and eventually accompanied by a public program aimed at identifying and advertising the true costs and the true value of water infrastructure. Priorities and planning must be set through public processes to gain acceptance;

3) <u>Developing of rational long-term fiscal objectives</u>: local utilities must aim toward

increased funding self-sufficiency with senior levels of government providing assistance based only on fulfilment of respective mandates; senior assistance should aim at supplementing communities with lesser abilities to pay to meet national standards and assisting with the implementation of any new, more stringent standards; the focus is to move away from the continued widespread subsidization of capital works.

6.3.1. Costs of Capital Replacement Programs

When discussing the dollars associated with rehabilitation of water systems, there are two separate issues which plague Canadians:

1) clearing up the current backlog of work;

2) implementing continuing long term programs of renovation/replacement.

According to the FCM (1984), the cost required to upgrade the existing systems in Canada and eliminate the backlog of work amounted to $76 per capita or about $1.75 billion in 1983. Today, accounting only for inflation, this figure would be closer to $96 per capita, or $2.2 billion nationally, which over a ten year period as the FCM suggests, amounts to $220 million per year in additional spending. According to the FCM (1984), of the total average annual water distribution system budget of $24.21 per capita in 1983, approximately $9.16 (or 38 percent) is for scheduled repairs and replacement. In 1992 dollars, this represents approximately $263 million per year nationally. Combined with the $220 million estimated by the FCM, spending levels near $483 million each year over the next ten years would be required just to clear up the problems which existed before 1984. This represents an 84 percent increase over current repair and replacement spending levels.

The costs and nature of longer-term distribution system replacement programs can vary widely and would require investigation for the cost versus benefits of each. MacLaren (1983) notes that in Britain the replacement program is based upon replacing different sized pipes at the end of their effective life: 100 years for pipes and service lines smaller than 300 mm in diameter; 120 years for 300 mm to 600 mm; and 150 years for pipes larger than 600 mm. Based on a similar 100 year replacement program and estimating the average system age to be 40 years, MacLaren (1983) calculates that total system replacement cost of $2,350 per capita for mains and services in Ontario would be spread over 60 years, resulting in a $40 per capita per year program (1983 dollars). However, MacLaren estimates that a combined program of renovation with minor replacement would be more realistic and only cost in the order of $25 per capita per year. MacLaren estimates current spending in Ontario to be only 25 percent to 30 percent of this $25 level. He goes on to estimate that initial inventory system and survey costs would amount to an average of about $10 per capita in Ontario with the costs in smaller communities closer to $15 per capita and in larger centres $5 per capita (MacLaren 1983). The costs outlined by MacLaren (1983) are summarized in Table 6.3.

Table 6.3: Summary of renovation and replacement costs in Ontario in 1983

Option	Program Period (1983 dollars)	Total Per Capita Cost (1983 dollars)	Per Capita Annual Cost (1983 dollars)	Monthly Cost Per Household (1983 dollars)
Total system replacement	60 years	$ 2,350	$ 40	$ 11.70
Renovation with minor replacement	60 years	$ 1,500	$ 25	$ 7.30
System inventories	5 years	$ 10	$ 2	$ 0.60

Source: MacLaren 1983

Combining the estimated national pipe quantities and typical sizes in this study with the unit prices for replacement provided by MacLaren (1983), replacement of the 130,300 km of water mains (including valves and fire hydrants) in Canada would amount to approximately $30 billion or about $1,430 per capita in 1983 dollars. The cost to replace the nearly 7 million services would amount to an additional $20 billion, or $929 per capita. Thus the total cost of replacement of the municipal distribution system would be approximately $2,355 per capita in 1983 dollars.

Based on an ENR 20 city construction cost index of 5,000 in 1992 and 4,000 as used by MacLaren in 1983, construction costs increased approximately 25 percent between 1983 and 1992. Thus the $2,355 per capita in 1983 dollars is closer to $2,940 in 1992. Based on the national average system age of 32 years as calculated in 1991, the cost per year for a total replacement program for all Canadian distribution systems would be $43 per capita, which is comparable to MacLaren's estimate, especially considering inflation and the relatively young overall age of Canada's water systems outside of Ontario. Based on the same inflationary adjustment, a national combined renovation and replacement program would cost $27 per capita in 1992 dollars, or approximately $620 million per year nationally. The cost to set up the nationwide system surveys would amount to approximately $290 million based on a 25 percent increase in costs since 1983 and a per capita cost of $10 in 1983. Again, the costs per capita in small centres would be more than those in larger centres. Assuming a nation-wide program of setting up inventory systems was also set up over the next 5 years at a cost per year of $58 million per year, this would amount to an additional $0.73 per month per household water bill. These costs are summarized in Table 6.4.

Table 6.4: Estimated national renovation and replacement costs in Canada

Option	Program Period	Total Per Capita Cost (1992 dollars)	Per Capita Annual Cost (1992 dollars)	Monthly Per Household Cost (1992 dollars)
Total system replacement	68 years	$ 2,940	$ 43	$ 12.50
Renovation with minor replacement	68 years	$ 1,836	$ 27	$ 7.90
System inventories	5 years	$ 13	$ 3	$ 0.73

While the required spending increases are large, there will be significant savings over time due to reduced breakage rates. Breakage repairs according to the FCM (1984) amount to $3.63 per capita per year for 30.4 breaks per 100 kilometres year. Based on an estimated 113,300 km of pipe in Canada in 1984, this amounts 34,400 breaks with a total repair cost of $76 million, or approximately $2,220 per break (1983 dollars). Accounting for inflation, the cost per break would be closer to $2,800 in 1992. Assuming the repair and renovation program reduces the average breakage rates down to 10 breaks per 100 kilometres per year as anticipated by MacLaren (1983), a saving of $53 million annually could be realized.

On the demand management side, Tate (1990) argues that long term water demand reductions can be realized through the installation of meters in the half of services not currently metered in Canada. According to Tate, the cost to install meters nationally would be in the order of $700 million based on $200 per meter and 3.5 million households.

6.3.2. Impact on the Average Canadian Water Bill

Water distribution systems are somewhat unique in that the two underlying management goals now being promoted tend to work in opposition to each other. Major policies aim at both solving the problem of over-consumption and eliminating price subsidies through increasing water rates. While the goal of water conservation to reduce consumption is honourable, it does create a dilemma for utilities whose only source of revenues is directly tied to water consumption; the greater the consumption, the greater the revenues.

In order for a utility to simply maintain revenues, any conservation efforts which reduce consumption will have to be accompanied by increases in the unit rates charged for water. However, to eliminate the current price subsidies and to provide needed capital for the anticipated replacement and renovation programs, water revenues cannot simply be maintained, but must increase. Thus, from a consumers perspective, the fact that increased conservation efforts will be met by ever increasing water rates will result in a perception of being penalized for actually conserving water! It is for this reason that public awareness of the reality of the current situation must be raised.

To illustrate the impact on the average Canadian's domestic water bill of a combined replacement and renovation program as promoted by MacLaren (1983), assume spending levels are raised to \$620 million per year as illustrated in Table 6.5 from the current \$263 million, with the consumer picking up the full tab. In Canada, the total annual water pumpage is 12.4 million cubic metres in communities larger than 1,000 in population. Assuming the \$357 million per year cost increase will be borne equally among all users based on percentage of water used, then the domestic users' share will be \$182 million, or 51 percent of the total which represents domestic flows as a percentage of the national total. Assuming the average Canadian household has 3.5 persons and uses 360 litres per capita per day, then on a monthly basis, the residence could be expected to use 37.8 cubic metres of water. Based on an Tate's (1990) average cost of $0.47 per cubic metre, the average Canadian monthly domestic water bill is currently in the order of $17.75. Should Canada's 23,000,000 domestic users be required to pick up the $182 million rehabilitation tab, the average Canadian would pay $7.91 more per year which translates into $27.70 per household annually, or $2.31 more per month on their water bill. The new monthly water bill would be $20.06, a 13 percent increase over the current billing.

Table 6.5: Cost comparison between various options for national rehabilitation

Description	Total Annual Cost	Annual Cost per Capita
Current scheduled repair/replacement budget	$ 263 million	$ 11
Spending level over 10 years to clear up backlog[a]	$ 483 million	$ 21
Long-term combined replacement/renovation program[b]	$ 620 million	$ 27
Long-term replacement of all distribution systems	$ 987 million	$ 43

a - based on FCM (1984)
b - as introduced by MacLaren (1983)

However, as Tate (1990) suggests, increased rates, combined with extensive metering and conservation programs, can be expected to decrease long term water demand in the order of 20 percent. For a utility to maintain revenues at the $20.06 per month level, the reduced consumption would mean the average unit price of water would ultimately have to be raised to $0.66 per cubic metre, a 41 percent increase over and above the current unit price of water. As can be seen in Table 2.4 of Chapter 2, this would put Canadian water prices about 25 percent above those in the U.S., but still less than many European countries.

6.3.3. Funding Sources

While the previous sections focused on the users picking up the full cost of any new programs directly, there is some justification for shared funding with higher levels of government. Such justification relies heavily on the degree to which any particular level of government's constitutional mandate is fulfilled by the funding program. Involvement of higher levels of government should come in two forms: direct funding and new legislation to support innovative funding mechanisms.

Direct funding is the most commonly used approach. In the future, financial assistance should continue to include conditional grant or low interest "infrastructure improvement" loans which aim at clearing up the worst of the current backlog. Cost sharing programs similar to those now being implemented in Ontario and Alberta can be developed nationally based on the rational benefits realized by the investment. Ideally, the goals of such programs should look beyond the short political time horizons and should provide guidelines for assessing system conditions and a fundamental groundwork for future capital works.

Any large scale funding programs should make funding or loans contingent upon a detailed assessment of the community's current water distribution system condition. The assessment would look not only at the physical condition of the water distribution systems, but the financial outlook based on the municipalities current rate structures and capital financing plans. Information system improvements such as defining common criteria for rehabilitation and replacement as well as common condition assessment criteria would allow comparison and overall monitoring of the progress of such a program.

The repayment of any local "water infrastructure improvement" loans could be through surcharges added to the water bill, but should be accompanied by an explanation to the consumer of the loans and improvements. Demystifying such loan programs and the necessity of them would be essential to prevent probable public backlash. Consumers must be made aware that in the long-run they will be paying less for the new capital programs now versus the higher maintenance, repair, and future capital works which would ultimately have to be paid later.

Williams (1984) suggests another option would be community contributions to revolving loan funds. Such a fund could be set up which every community in a specified geographic area could pay into, based on a provincial capital recovery surcharge. When a rehabilitation need arises, a community could draw on the fund for required upgrading monies. Although such resource pooling may be attractive, the bottom line remains that communities will have increase revenues to make funds available to pool.

One other popular source of revenue is the development cost charge levied against developers wishing to tie into existing systems. Although a justifiable source of funding, the charges must remain equitable so that the developers pay their true share of the actual rehabilitation, especially considering that these charges are ultimately charged back to the new residents in the form of higher housing prices. Any over-charging for the simple purpose of convenient revenue generation would result in new residents paying a disproportionate share of other's past problems.

6.3.4. Economic Benefits of Water Distribution System Investment

While the costs may seem high, reinvestment in our water infrastructure can be looked on in a positive light as the natural continuation of a process that was started after World War II. From a national perspective, development improved the standard of living in North America and provided both the infrastructure backbone required for development of industry as well as much needed employment in public works projects. While this course of action has largely been abandoned as evident in the shifting of funds out of federal infrastructure programs, recent political changes in both the United States and Canada signal hope that the situation may be changing. President Clinton has announced publicly on numerous occasions that he plans on introducing a $20 billion program aimed at improving America's roads, bridges, and lifeline systems, and estimated to create approximately 25,000 jobs per billion spent. While this will not go far considering the American's annual funding shortfall of $9 - $11 billion estimated by Dunlop (1983) it is a good start. In Canada, the new Liberal government under Jean Chretien has announced a similar $2 billion program aimed at all physical infrastructure systems. Federal funds would be matched by equal provincial and local contributions resulting in a total program approaching $6 billion over the next two to three years. Again, while a promising start, the program will only begin to solve the current $30 billion backlog of public works and the contributions of the debt-burdened provincial and local governments are by no means assured.

At the heart of the new federal program is job creation. A 1983 study shows that investment in public works results in 35 to 40 person years of employment and $250,000 in expanded local business for every million dollars invested (Environment Canada 1983). After accounting for the fact that a million dollars in 1983 is equivalent to $1.25 million in 1992 dollars, an annual spending increase of $357 million per year to implement a national combined replacement and renovation program for water distribution systems would still create approximately 10,000 jobs and generate $71 million worth of local business. In addition, a savings in unemployment insurance benefits paid out for the 10,000 jobs in the order of $105 million could be realized annually, based on an average of $202.75 per capita per week paid out in unemployment benefits (U.I.C.) in 1988 (Canada World Almanac 1990).

As can be seen in Table 6.6, the $357 million increase in expenditures could result in long term benefits totalling $229 million from reduced breakage rates, annual U.I.C. savings, and local economic development. Of course the benefits from reduced breakage rates would not be realized until later years when the overall system characteristics are improved. However, economic impacts from job creation would be realized early.

It is also from this job creation aspect that local and provincial bodies should continue to lobby the federal government since employment and regional development are both within the federal jurisdiction. From this perspective cost sharing in the order of 25 to 35 percent can be justified.

Table 6.6: Costs and benefits of a combined replacement/renovation program

Description	Total Annual Cost
Combined National Renovation / Replacement Program	$ 620 million
Current National Scheduled Repair / Replacement Spending	$ 263 million
Net increase in spending required	$ 357 million
Annual savings in water main breaks	($ 53 million)
Annual savings in U.I.C. benefits paid out	($ 105 million)
Local economic development	($ 71 million)
ACTUAL NET ANNUAL COST OF PROGRAM	$ 128 million

6.4. Summary

This thesis has focused on improving the information on existing systems through the use of historical data which may have been overlooked and to outline the main problems and available solutions, eventually synthesizing them into a framework which can be used in Canada. There is nothing new in the information, and as Grigg (1988) points out the current problems do not necessarily require the generation of new ideas but rather the effective application of already developed ideas. There is nothing magical about the solutions; the real trick will be to get these things up and running by matching the appropriate technologies to the appropriate situations. Levels of sophistication should be considered in the management of systems: the small village of 500 will not need nor be able to operate the sophisticated models of the large cities of 500,000, yet the small villages of 500 should still be included in a larger global model which may be operated on a regional or provincial basis. The current information age brought about by the new "personal computer generation" and improving education levels of operators means that both large and small communities can expect higher levels of management sophistication than what exists today. The tasks are not impossible, but the political will must be there to implement them.

CHAPTER 7: CASE STUDY

7.0. Background

The Corporation of the District of Pitt Meadows is situated on the confluence of the Fraser River and the Pitt River on the eastern edges of the Vancouver CMA. The District was incorporated on April 1, 1914 and encompasses and area of 5004.5 Hectares, with a 1989 population estimated at 9,546 (GVRD 1990). Compared to other small communities in Canada, the District is growing extremely fast (see Table 7.1), as is much of the Lower Mainland, and can expect between 200 and 400 new residents per year.

Table 7.1: Pitt Meadows recent population growth

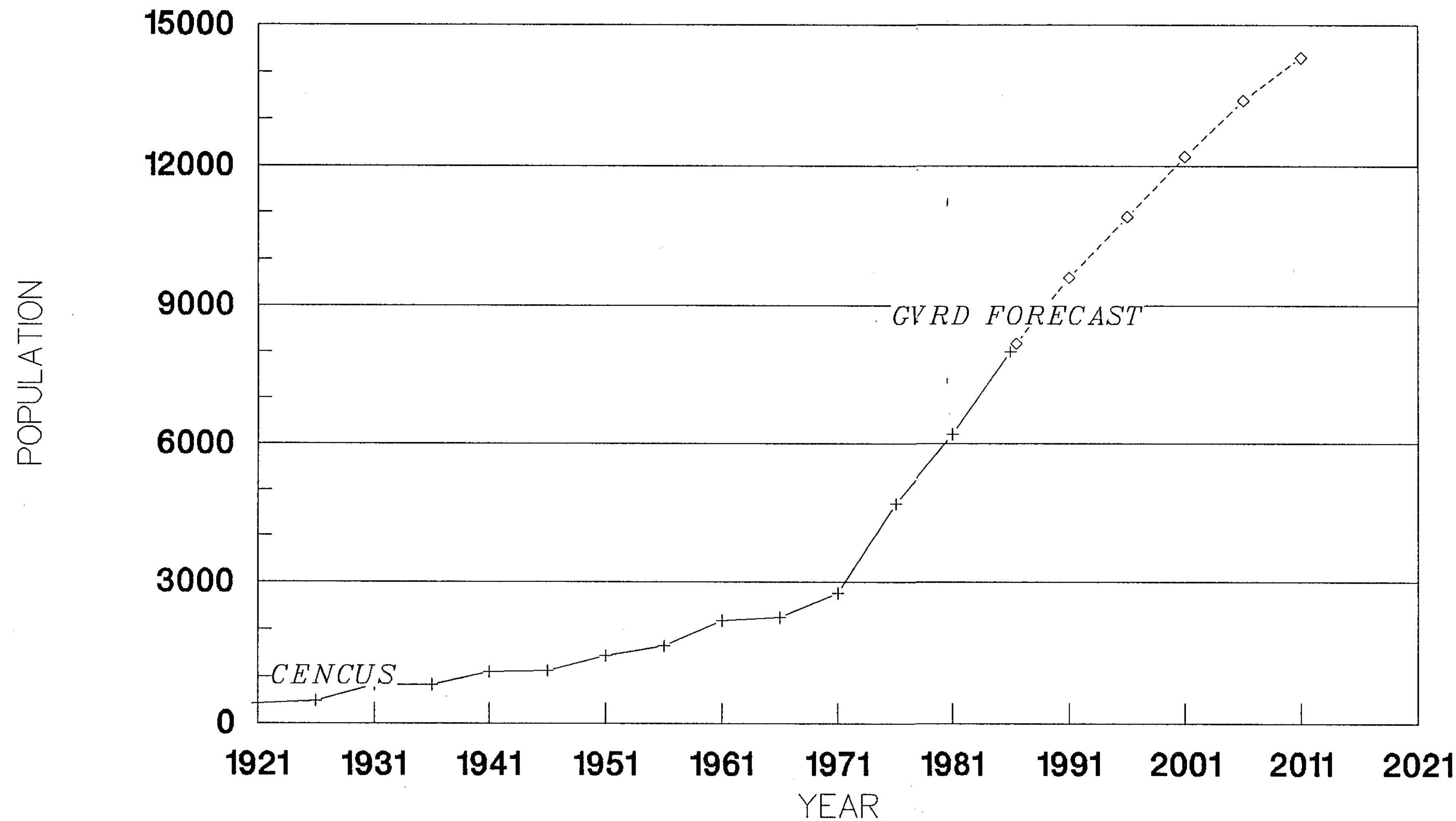
PERIOD	POPULATION GROWTH IN PERCENT	
	Pitt Meadows	National Average (Small Centres: pop. < 10,000)
1971 - 1976	69	11
1976 - 1981	32	8
1981 - 1986	29	2

Source: Adapted from population data; B.C. Municipal Affairs 1951 - 1988

Although a substantial percentage of the current distribution system was in place in the 1950s and 1960s, rapid growth did not occur in the District until the 1970s as seen in Figure 7.1. In 1971, while it had less than 30 percent of today's population, the District had over 65 percent of the current pipe in the ground. Thus, since the 1970s the water distribution system has been undergoing infilling and relatively slow expansion.

Compared to other municipalities in the Greater Vancouver area, property values in Pitt Meadows remain relatively low, reflecting a large rural influence. The 1989 tax roles included 3,808 assessed properties with an average value of approximately $87,000.

Figure 7.1: Pitt Meadows population growth



Source: BC Municipal Statistics (vary); GVRD 1990
File: PITTPOP.CAL

This compares to the total of 455,286 properties in the Vancouver CMA with an average value of $174,178, and 116,677 properties with an average value of $232,365 in the City of Vancouver itself (GVRD 1990).

7.1. Water Consumption

The water system is somewhat unique in that it serves an urban area representing about 76 percent of the population and a rural area with 24 percent. The connection rate in Pitt Meadows is 100 percent, meaning the entire population is served from the District's distribution system.

Table 7.2: Pitt Meadows water consumption in 1990.

Average Daily Flows:

WATER	7336 m^3/d	- Domestic	5135 m^3/d
		- Commercial/Institutional	734 m^3/d
		- Industrial	1100 m^3/d
		- Other	367 m^3/d
SEWER	3260 m^3/d		
DIFFERENCE	4076 m^3/d (UNACCOUNTED FLOWS)		

Unaccounted Flows: (as percentage of water flows)

Pitt Meadows	56 %
National Avg.	26 %

Source: Data adapted from IWD (1990)

The average daily flow for the District is 7,336 m^3/d with only about 44 percent of this returned to the sewer system, leaving 56 percent unaccounted for (see Table 7.2). Some of the unaccounted water can be attributed to high consumptive uses such as greenhouses and agricultural type uses. However, the most obvious reason is the lack of sanitary sewers in areas which are served by the water distribution system. In Pitt Meadows in 1988, there were 82 kilometres of water mains, yet only 26 kilometres of sewer mains. This is a reflection of the fact that the water system supplies a large number of rural users with individual sewage systems and highly consumptive agricultural uses. Thus a significant flow is not returned to the District's sewer system.

Accordingly, per capita water consumption in the District is quite high as can be seen in Table 7.3. Still, when factoring out the high commercial and industrial consumption, domestic consumption in the District is about 36 percent above both the provincial average and the national average for small communities, and 68 percent above the overall national average.

Table 7.3: Comparison of water consumption with national and regional data

COMMUNITY	CONSUMPTION (l/d/capita) Total	Domestic
Pitt Meadows	843	590
B.C. Average	722	429
Canadian Average (all communities)	688	351
Canadian Average (< 10,000 popn.)	668	434

Source: Data adapted from IWD (1990)

7.2. Water Rates

Within the urban area, the majority of consumers are residential or commercial users and are governed by a very low flat rate for water. Based on 1991 rates, single occupant residents are charged $27 per year and multi-occupant residences $36. Commercial users rates vary among type of use, ranging from $12 per year for a church, to $90 per year for a slaughterhouse, with the average rate being about $50 annually.

The rural area is metered and the rate structure includes a minimum charge for domestic use with a constant unit rate above a set volume, and a declining block for commercial and industrial users. Domestic users pay a minimum of $18 for every six month period for 53,000 Igal (240 m^3 or 40 m^3 per month) from January to June or 60,000 Igal (272 m^3 or 45 m^3 per month) from July to December. Consumption above the set volume is charged at a constant rate of $0.24 per 1,000 Igal ($0.053 per m^3). Except for golf courses which pay a minimum 6 month charge of $240, commercial and industrial users pay a minimum of $18 per 6 month period. Consumption charges decrease with increasing blocks, ranging from $0.40 per 1,000 Igal for the first block between 0 and 20,000 per 6 month period, to the highest block where the charge is $0.24 per 1,000 Igal for any volume used over 175,000 Igal (see Table 7.4).

Table 7.4: Pitt Meadows commercial water rates

CONSUMPTION BLOCK	WATER RATE Per 1,000 Igal	Per m^3
0 - 20,000 Igal	$0.40	$0.09
20,001 - 50,000 Igal	$0.35	$0.08
50,001 - 100,000 Igal	$0.30	$0.07
100,000 - 175,000 Igal	$0.26	$0.06
over 175,000 Igal	$0.24	$0.05

Source: District of Pitt Meadows 1991 Water Rates

7.3. The Water System

The District receives its water from the Greater Vancouver Water District, a regional supply and transmission system that supplies water to approximately 1.5 million people in 20 municipalities and 3 electoral areas. The GVWD, by virtue of a number of high elevation sources in protected water sheds, distributes water requiring only chlorination and little or no pumping at wholesale rates which are among the cheapest in Canada. Pitt Meadows receives its water from three connections to a 750 mm (30") GVWD main along the Lougheed Highway which also serves Maple Ridge to the east. Delivery pressures during peak periods at the three locations vary from 76 to 108 psi and are expected to decrease in the future with increasing demands from Maple Ridge (CBA 1981). Because the District is supplied from a pressurized and treated supply, there are no pumps, treatment works nor reservoirs in the District.

The urban area is served by a system which provides flows and hydrants for fire protection (Figure 7.2). The rural system consists of many small diameter pipes, including 50 mm and 100 mm diameter, and as such provides only domestic and industrial water service with no fire protection. The system age is typical for a community of this size.

Most pipe was installed after World War II and based on the Municipal Utilities surveys of 1951 and 1961 and provincial municipal statistics, the data in Table 7.5 has been accumulated. Based on this information, the average age of the overall system is 31 years. Of the 82 kilometres of pipe in the ground in 1988, over 50 kilometres is older cast iron or small diameter galvanized iron. The majority of the remainder is ductile iron with a small fraction of asbestos cement.

Figure 7.2: Pitt Meadows existing pipeline network

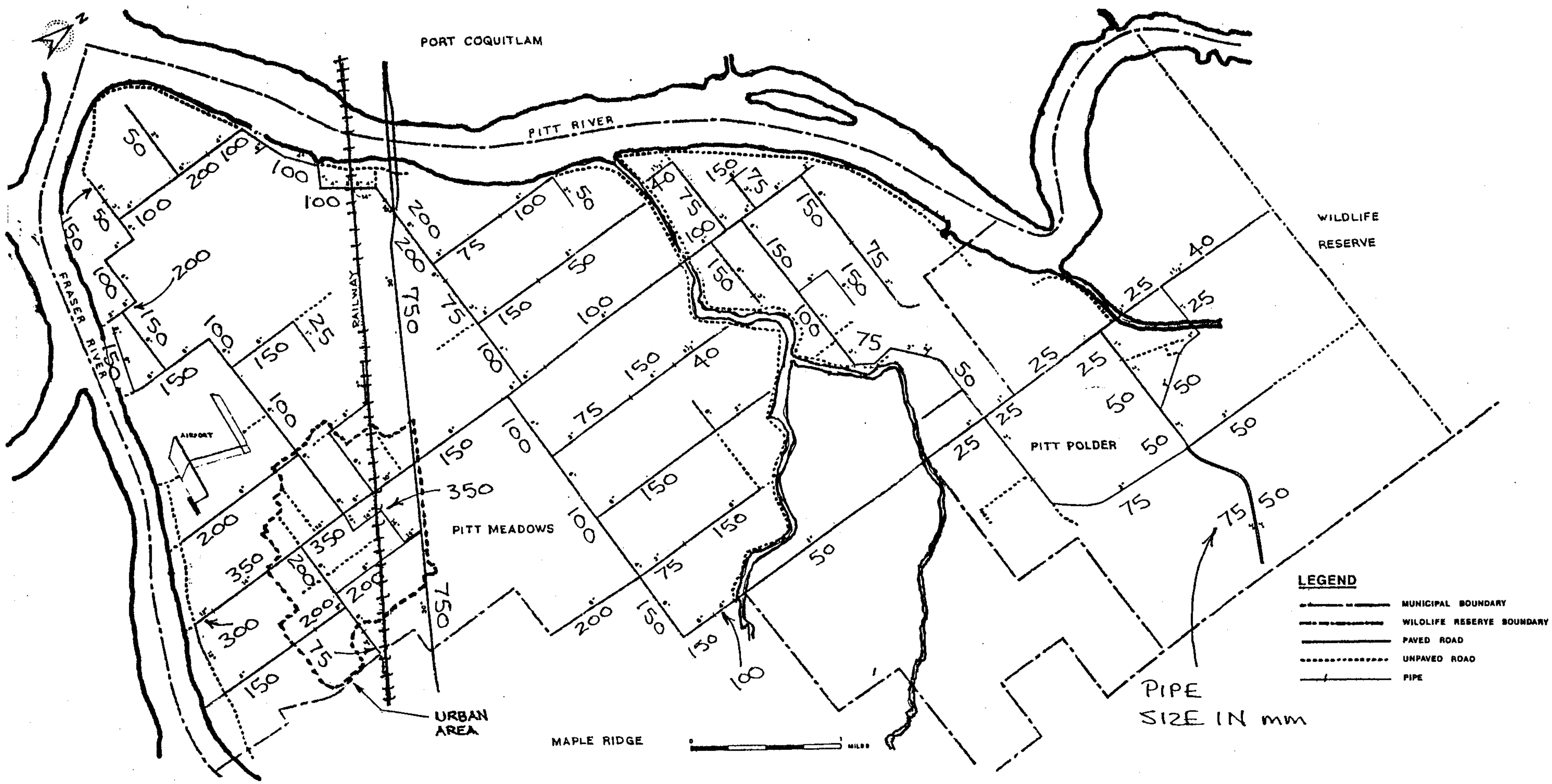


Table 7.5: Historical information on the Pitt Meadows water system

YEAR	POPULATION SERVED	PUMPAGE (l/d/capita)	LENGTH (km)	PIPE DENSITY (persons/km)	---- SYSTEM BREAKDOWN ---- Length	Material	Sizes
1951	1100	-	40.4	27.2	40.4	Cast Iron	1" - 6"
1961	1750	822	51.6	33.9	40.4	Cast Iron	1" - 6"
					11.2	Galvanized	1"
1971	2771	-	58.2	47.6	-	-	-
1981	6209	-	72.0	86.2	-	-	-
1988	8700	843	82.0	106.1	-	-	-

Source: MU 1951; MU 1961; B.C. Municipal Statistics 1971, 1981, 1988

As can be seen in Table 7.6, the pipe sizes vary widely from the urban to the rural areas.

Table 7.6: Breakdown of Pitt Meadows water system by pipe size in 1981

PIPE SIZE	PERCENTAGE OF LENGTH IN RESPECTIVE AREA URBAN	RURAL	TOTAL SYSTEM	CANADIAN AVG. IN 1961
< 100 mm	0	43	37	2
100 mm	0	22	19	12
150 mm	16	20	20	55
200 mm	36	5	10	16
250 mm	6	4	1	4
300 mm	0	1	1	8
> 300 mm	42	8	13	3
TOTAL	100%	100%	100%	100%

Source: Pitt Meadows data extracted from CBA (1981); Canadian estimate from data base MU (1961).

The District maintains large mains in the urban area to provide fire flows, while in the rural area nearly 70 percent of the pipes are smaller than 100 mm, with nearly 17 kilometres being 25 mm and 50 mm.

At the present time, the District does not have long range plans for the eventual replacement of the existing water system and as of 1991 was putting together its first ever 5 Year Capital Improvements Plan. The most current assessment of the existing distribution system was a study done by a private consultant in 1981 (CBA 1981). The study was undertaken for the B.C. Ministry of Environment, Inventory and Engineering Branch pursuant to the Canada - British Columbia Agricultural and Rural Development Subsidiary Agreement from July, 1980 to January, 1981.

The main focus was not on a system wide assessment of condition, but rather concentrated on the system improvements which would be required to remove constraints on future rural agricultural and commercial developments and the benefits which would be associated with such improvements. In fact, the Highland Area which is the District's main urban area and town centre, was excluded from the study area as it was outside the Agricultural Land Reserve, and was assumed to have an adequate water distribution system.

The existing rural economic base relies heavily on water and includes dairying, beef feeding, hog production, nurseries, specialty crop production, and a large number of 5 and 10 acre hobby farms. Future increases in hog production, nurseries and greenhouses, and rural residences are anticipated. The 1981 study includes:

1) a projection of rural development over a 5 year period;

2) an evaluation of future water demand;

3) preliminary design and costing of the water supply system;

4) benefit : cost analysis of project alternatives.

Future demand estimates were extrapolated from the existing consumption records and applied to the future development scenarios. A computer analysis of the pipe network was used to determine sizes for water mains requiring upgrading or extending and cost estimates were determined.

The projection of future rural development and the benefit : cost analysis were both based on a questionnaire circulated in the District as well as census and economic information gathered from various government bodies. From the questionnaire, benefits, on-farm costs, and probable future development for each respondent could be determined. Direct benefits such as those resulting in increased commercial output or residential development were identified, as well as secondary benefits associated with improved fire protection and potential industrial development.

Much of the system in the study area is undersized with 1" to 4" (25 mm to 100 mm) pipes and the District has had to refuse connections due to lack of peak period pressure and capacity. In addition, one part of the system is isolated from the rest of the system fed from the GVWD: the source being a lake susceptible to large fluctuations in water quality, the water being untreated and unmetered, and the distribution system consisting of some unburied PVC pipe and many 1" to 3" (25 mm to 75 mm) mains. The District has proposed connecting any isolated sections of the system to the main system and upgrading any 4" (100 mm) trunk mains with 8" or 10" (200 mm to 250 mm) pipes.

The study recommends three pipe upgrading scenarios based on the hydraulic and economic analysis done. The estimated costs of the three scenarios proposed ranged from $2.1 to $5.1 million (1981 dollars) and result in benefit:cost ratios ranging from 1.3:1 to 2.6:1.

According to the District Engineer (Lowry 1991), the District intends to direct its efforts toward the continued upgrading of capacity as recommended by the study. Funding is through the Canada - B.C. Agricultural and Rural Development Subsidiary Agreement with the District paying 25 percent and the senior levels of government paying an equal share of the remaining 75 percent. Negotiations are continuing to secure future funding under the program as the District is highly dependent on the program to complete the rural works.

7.4. Record Keeping

Record keeping of breaks and system problems in the District is not systematic, with most of the records in the hands, heads, and daily journal of the public works superintendent. The District practises a loose "rule of thumb" method of pipe replacement similar to many smaller communities. In general, when a section of pipe is deemed by the superintendent, based on his discretion and experience, to have too many breaks, the section is put on the list for replacement. While leak and breaks are recorded in daily journals and repair reports, the information is not systematically tracked (Cross 1991).

The district has recently purchased a p.c. based computer G.I.S./C.A.D. system for approximately $20,000 but, due to the enormous time demands placed on the staff due to rapid growth of the District, formal plans regarding what to do with the system and the information input are only slowly being formulated. In addition, the enormous staff and man-hour commitment required to implement and get data into the system were under-estimated at the time of purchase, so the system will probably not be fully operational for a few years (Lowry 1991). As of late 1991, about 60 percent of the system was recorded on hard-copy as-built drawings, with about 40 percent of these now on the C.A.D. system.

The District's record keeping is for now limited to written reports and journals. Reports of leaks and breaks and their subsequent repairs are recorded, but are not easily accessible for planning or system monitoring purposes. Overall system maps have been developed as well as system future plans for looping and upgrading. No overall system assessment for breaks, nor any system wide leak survey has ever been carried out nor is anticipated within the near future. As can be expected, no replacement strategy models (descriptive, predictive, nor physical) have been developed nor utilized. For now, the main indicators of system deficiencies are inadequate system flows and/or pressures.

7.5. Staffing Levels

From a staffing perspective, the District employs 13 people in its Public Works Department and 3 in its Engineering Department. The Public Works Department includes one professional/technician in a supervisory role and 12 field personnel. The Engineering Department employs 3 professional/technicians and no field personnel. The staff works to operate and maintain a variety of systems, with none dedicated to any particular system. In general, work on the water distribution system accounts for about 20 percent to 25 percent of the staff time (see Table 7.7).

7.6. Funding

Funding for the water system operations and day-to-day maintenance comes largely from user charges with any surplus going into the District's reserve fund. The reserve fund is a sizeable general purpose fund used by the District, not necessarily for utility improvements, with the surplus contributed by the utility varying from year to year (Lowry 1991).

Table 7.7: Estimated staff work load split among systems in Pitt Meadows

SYSTEM	PUBLIC WORKS DEPT.	ENGINEERING DEPT.
Roads and Storm	50 %	50 %
Water Distribution	20 %	25 %
Water Treatment	1 %	1 %
Sewer Collection	20 %	20 %
Garbage Collection	0 %	1 %
Miscellaneous	4 %	2 %
	----------	---------
TOTAL	100 %	100 %

SOURCE: Lowry 1991 (estimate)

Fiscally, the District is in relatively good shape. Debt financing is not frequently utilized to finance system improvements and at present the only outstanding debentures are on some relatively minor sewer system improvements. Provincial subsidies in the urban area of the District account for approximately 25 percent of system revenues through revenue sharing water/sewer capital grants. General revenues through taxes account for an additional 30 to 35 percent, while development cost charges on new subdivisions can pay up to 30 percent of upgrading costs. User charges account for approximately 20 to 25 percent of total system revenues, with most directed toward operations rather than capital improvements. In rural areas, the ARDSA grants cover up to 75 percent of system improvement costs, development cost charges can account for up to 15 percent, and the remainder typically comes from general revenues. Assuming the needed improvements have been sufficiently identified and funding sources do not significantly change, revenues are expected to meet the desired expenditures (Lowry 1991).

The District does have a program in place for the systematic cleaning and lining of problem mains, but to date the program has never been implemented (Cross 1991). The District does however carry out annual flushing operations.

7.7. Rehabilitation and Replacement Programs

Apart from the need to replace pipes due to limited capacity, the District has not identified a need to replace any significant lengths of pipe due to deterioration and/or high breakage or leakage rates. Currently, approximately 13 kilometres of pipe need to be replaced due to capacity concerns, while only 1.3 kilometres need replacing due to deterioration, with approximately half being asbestos-cement pipe. As in other parts of the Greater Vancouver area, the distribution water is aggressive toward A.C. pipe, tending to soften it to a point of failure. Most of the A.C. pipe in the District has already been replaced, and all new pipe installations are ductile iron.

From a health perspective, the major concern has to do with excessive coliform bacteria counts in the water. Probably much of this is due to a loss of chlorine residual between the source at the Coquitlam Reservoir and the points of distribution, rather than with the distribution system itself. Concerns regarding high metal concentrations (ie. iron or lead) or asbestos cement are not pronounced at this point in time.

7.8. Discussions

As the information gathered on the District's system is quite general, a number of important observations can be made. While a much more exhaustive investigation would be required to assess the problems in detail, it is possible to highlight the potential for general improvements.

Information on the water distribution system is limited, though the District has taken definite steps to remedy this through the recent hiring of an engineering technologist, as recommended in a report by a management consultant to help alleviate the heavy workload put on the development engineer. The technologist is responsible for drafting, records, design, dealing with the works yard, and assistance on capital works.

It has been noted that when people come in to inquire about the services to a particular parcel, on occasion there has been no records and someone must physically go out in the field and inspect (Cross 1991). The recent acquisition of the CAD and GIS equipment is promising as the District eventually plans to interconnect the legals, infrastructure, and tax information. To date information transfer is going well, but it should be noted that approximately 10 percent of the system information is not on paper but is carried by the senior public works superintendent, who is soon to retire. A computerized maintenance management system in the public works yard is being set up to track timesheets, unit costs, repair costs, etc. and eventually may include watermain repairs. However, the community is basically on its own when it comes to inputting and organizing the information. This is one area where especially the smallest communities could use assistance and guidance in wading through the new equipment and programs available and in setting up a system which is useful from a operations and management standpoint.

The higher than average population growth rate in the District means that more and more people will be connecting to the existing system, increasing the need for a reliable system capable of providing both adequate fire and consumptive flows. The 1981 report on system expansion used assumed "C" values for pipe roughness and as such may not have reflected accurately areas with reduced capacities due to deteriorating hydraulic characteristics within the pipes. Pipe flow tests utilizing the existing hydrants would be useful.

Due to the relatively low density of most of the District and the low property values, liability due to flooding caused by main breaks is limited. However, liability concerns regarding fire protection do exist and caution should be exercised respecting the proposed extension of fire protection out to the rural area, which may be prone to inadequate flows during peak irrigation periods.

The high unaccounted water volume is a concern, though it can be explained by high consumptive uses and the fact not all consumers are served by sewer systems which measure the return flows. A water audit to confirm leakage and account for all distributed water would be invaluable in assuring that the system is sound. Unfortunately, unless the District plans on metering all users of the system, long term day to day monitoring will be difficult.

Based on pipe sizes, the problems of limited capacity investigated in the 1981 report (CBA 1981) are quite easily seen. A number of lines are undersized based on current municipal standards for fire flow. Of course, the rural component is aimed at providing flows to meet the domestic/commercial/agricultural needs rather than fire flows. The municipality is proceeding to replace sections of the system restricted by small diameter pipe.

While health concerns regarding the distribution system per se have been relatively non-existent, the conditions which brought on elevated levels of coliform bacteria can lead to increased bacteriological growth within the distribution system. While the problem will likely be solved by increasing the residual chlorine in the system, regular programs of cleaning and lining mains can eliminate the tubercles where growth may occur while at the same time increasing the hydraulic capacity of the mains. The cleaning and lining program which was set up should be carried through.

The water prices charged to the residents of Pitt Meadows are among the lowest in the country. Based on the rate structures and consumption rates for the District, the typical residential and commercial users are paying between \$0.055 and \$0.09 per m^3. Compared to the national average of about 0.47 per m^3, water in Pitt Meadows is very cheap. Undoubtedly, this low price contributes significantly to the high consumption rates observed in the community.

Considering the GVRD wholesale water rate is around \$0.05 per m^3, it is easy to see that there is little built into the District's water rates to provide for the eventual replacement of the system. This is typical of most communities in Canada. Based on unit prices provided by MacLaren (1983) and CBA (1981) and adjusting for inflation using the ENR index, the replacement costs for the Pitt Meadows distribution system would be in the order of \$25 million, and the services in the order of \$16 million. Using MacLaren's methodology, with the average age of the system 31 years and assuming a 100 year replacement cycle, the replacement would be completed in 69 years. Based on the domestic users paying their share of this, the average annual water bill would have to increase by about \$143 from the current level of \$33. However, MacLaren (1983) notes a combined repair/renovation program could be carried out at about 60 percent of the replacement program. In Pitt Meadows, this would cost $90 per household per year. This is very close to MacLaren's figure of $25 per capita per year in 1981 after adjusting for an average household size of 2.82 in Pitt Meadows and a 25 percent increase in costs due to inflation based on the ENR index. However, in the case of Pitt Meadows this translates into more than a tripling of the average water bill, from the current $3 per month to $10. Such an increase would increase the current rate per m^3 from about $0.07 to $0.22, which is still less than half of the national average.

In any case, such increases would be very difficult for the public to swallow, especially after years of extremely cheap water. It would take a lot of education and a real political will to carry out such measures. In addition, to properly carry out any revamping of the rate schedule, it would require metering of the other half of the District; at $250 per meter, new meters for each households in the community would cost in the order of $850,000. The Provincial government could play a key role in financing some of the short term requirements based on its current cost sharing formulas. However, the trend of senior government seems to be, and perhaps well should be, to move out of local water system funding for system replacement. Pitt Meadows should consider a plan for eventual self-sufficiency in water system management and also move away from supplementing general revenues with revenues from the water system. Of course, it will be difficult for a small district to do on its own. Such measures should be promoted by the Province and the GVWD with input and cooperation from the other member communities in the GVWD.

7.9. Summary Recommendations

In summary, more information is required to allow a conclusive assessment of the condition of the Pitt Meadows water distribution system. Information is being gathered, but needs to be amalgamated from reports to be useful. Although the community is making great strides to improve its management systems, guidance on the information to be input and standards of assessment are required. In the community, average consumption rates are very high and the water rates are both very low and structured in such a way as they do not promote conservation. Both water metering and inclusion of a charge for capital replacement in the water rates should be considered. Of course any such action will require substantial public education and input. A water audit should be carried out by the District to reconcile the high unaccounted for water. The rapid growth of the community means the existing system will be called on to serve more and more people, therefor measures should be taken to assure it is reliable and will serve the community well in years to come. Finally, there should be more information sharing and the promotion of ideas among the communities both in the Greater Vancouver area, as well as in the Province of B.C. and the nation as a whole.

A number of recommendations may be made to assist the municipality in improving both the efficiency and effectiveness of the system:

1) add meters to the system and increase the water rates to both reduce consumption and increase revenues for eventual capital replacement; such a program should be carried out in a rational and phased manner with input from the public;
2) communicate with other communities of similar size and/or growth characteristics as well as larger centres (ie. Vancouver) to compare consumption, water rates, and rehabilitation programs;

3) make upgrading of the existing system a priority to accommodate future growth;
4) implement a replacement and rehabilitation strategy; this will be based on carrying through the program already in place as well as continuing with the recommendations on the distribution upgrading report of 1981; less emphasis will be on property loss due to flooding as development densities are relatively low;
5) consideration should be given to the additional liability concerns and potential costs should fire flow and fire fighting service be extended to the rural area;
6) concentrating on the growth of the system and enhancing its capacity should remain a priority, with some consideration given to the reliability of the system in the urban Highlands area;
7) the District should consider a number of options to reduce its high unaccounted for water:
    a) water audits to assist in locating leakage and lost water;
    b) metering to both help reduce consumption and to assist in the audit calculation;
8) consider increasing water rates to include eventual capital replacement;
9) upgrade small diameter iron and galvanized pipes as recommended in the 1981 report to help enhance economic growth potential;
10) consider the need for eventually replacing the high percentage of pipes in the system which may be over 40 years old; collect installation date and repair/replacement data on the system if available;
11) consider in the urban area increasing land use densities, filling vacant lots, and infill if feasible as the 106 persons per kilometer of pipe served is quite low, although it is reasonably good considering the large percentage of rural users;

12) continue with the development of the p.c. database and management systems and attempt to get all records on the system from the hardcopy paper records;
13) introduce preliminary descriptive analyses to help pinpoint system breakage or leakage problem areas;
14) carry on the planned cleaning and lining program to help reduce potential health and flow problems;
15) maintain current staffing levels, but in the short-term hire on part-time help to assist in the data entry, should budgets allow;
16) revamp the funding and financing mechanism to separate the water system funding from general revenues and prepare for the real possibility of reduced funding levels from senior levels of government.

CHAPTER 8: CONCLUSIONS AND RECOMMENDATIONS

8.0. Overview

Applied to the Canadian context, the developments in pipe technology over the past century will be major determinants in the deterioration of piped systems over the next 25 to 50 years. Larger, older cities with significant lengths of old mains, may not necessarily be in a significantly worse state than their newer counterparts. Small towns and cities which have developed systems since the 1950s using largely small diameter pipes and new, less durable materials, may develop comparable problems over relatively short periods of time. Thus, while the reduction in material and installation costs associated with modern materials and designs may have significantly accelerated the expansion of water systems over the past 30 years, it may also have accelerated the need for rehabilitation and replacement.

8.1. Application

The basis of this thesis has been to exhibit through the study of water distribution systems the basis upon which a rational national policy on infrastructure rehabilitation and restructuring can be developed. Many of the principles outlined can be applied to roads, sewers, water treatment, sewage treatment, and a host of other systems which make up the physical fabric of our nation. Water distribution systems were specifically investigated to illustrate the shortcomings of current infrastructure management and financing which is evident to some degree in all the physical systems in Canada.

While they are in decline, our water distribution systems, and indeed most of our other large scale infrastructure systems, are by no means on the verge of imminent catastrophe. However, the small leaks and cracks in the systems are slowly showing and should they remain unchecked, there will be significant health, economic, and fiscal consequences down the road. It is prudent to begin planning for the impending fate of our infrastructure systems now, and a logical place to begin is with organizing the information required to make useful decisions and with improving both the technical and financial systems which will be required to carry out the rehabilitation.

As with water distribution systems, all infrastructure management information must be detailed enough and in a readily usable form to make useful decisions. Policies should not only aim at rationally replacing, rehabilitating, or renovating system components which are wearing out, but should recognize and improve methods of tracking system condition, improving performance, minimizing risk, collecting revenues, maintaining equity, and ultimately serving the end user better. Such policies will reach across a variety of administrative and legislative levels, and as such should be developed on a national level while remaining flexible enough to be adopted and administered at the provincial and local level.

8.2. Recommendations and Solutions

The historical development of Canadian infrastructure systems is not insignificant when focusing on today's solutions. Economic and health concerns were at the heart of the development of these early systems and advances in system development was paralleled by unprecedented increases in the standard of living in our nation. The historical development of piped water distribution systems is also significant for study in that much of the materials originally installed 75 to 100 years ago are still in service and will soon require replacement.

While most systems have developed under public control and management, the involvement of the private sector in future systems management cannot be overlooked, especially with the ability of the private sector to raise capital for rehabilitation programs. Strong legislation and regulation with respect to servicing and water quality can assure standards are maintained.

There is a definite need to consider improvements to fire flow considerations in water systems, especially in small communities where many do not meet the current insurance industry standards and liability concerns are growing. The courts in Canada are placing even more responsibility and liability for the short-comings of existing systems directly on the shoulders of the public utilities. While legislation may be introduced to reduce the communities exposure to such liability, the fact of the matter remains that inadequate systems can prove to be very costly in terms of damages, lost industry, and waning public support.

The solutions will involve specific strategies aimed at specific problems. A joint task force involving the business, design, and construction communities as well as utility managers, universities, and all levels of government should be set up to effect the proper strategies, better involve the public, and continue the research first undertaken by the FCM. Huge sums of money distributed in a broad fashion is neither appropriate nor realistic considering today's fiscal atmosphere. The biggest problems are often concentrated in a relatively small number of communities. In addition, the solutions will vary widely based on community size, system age, regional considerations, and abilities to pay. Large cities such as Toronto, Montreal, and Winnipeg have the resources to effectively tackle and identify their problems whereas small communities such as Pitt Meadows must consider means of not only identifying solutions, but tracing the problems. Non-structural solutions such as water rate restructuring, demand management, water metering, and infilling can be especially effective in the small communities by must be introduced to the consumers in a rational and straight forward manner.

Current research by government, universities, and the private sector should concentrate on developing simple, effective, and economical infrastructure management systems for personal computers. Guidance manuals based on the Canadian context must be developed to assist local operators and governments in planning for the secure future of these lifeline systems. University programs in engineering and planning must begin to recognize the importance of maintaining the billions of dollars already invested in the ground. Research should also aim at improving pipe monitoring and replacement techniques for relatively small diameter 6" (150 mm) and 8" (200 mm) sized cast and ductile iron pipes which make up the majority of the pipes soon to require replacement. Research should also consider solving the predominant problems faced by Canadian systems: failures due to frost and temperature effects, poor quality construction and material failures due to corrosion and age. Reduced strength in new plastic pipes and the reduced corrosion resistance of thinner walled ductile iron pipes will dictate more intensive long-term monitoring of the performance of these newer pipe materials. Continued investigation into the mechanisms of structural failure will also prove valuable. Benefits can come from reducing the high breakage rates of small diameter 150 mm to 200 mm mains and realizing that the nature of breaks is spatial in nature, with most breaks recurring in areas of previous break history. Such developments can help to channel replacement resources to the appropriate problem areas. Research strategies which also include more global factors, such as liability issues, can also improve overall management of systems. As O'Day (1984) suggests, areas of high risk of leaks but low risk of damages can best be served by leakage control while areas of high risk of leaks and high probability of damages should be considered for outright replacement. These examples of concentrating on the specifics of the problems and engaging the appropriate technologies to the appropriate problems will only help to effectively solve the current crisis.

Long term structural and non-structural improvements must be made and implemented with the understanding from the public bodies and the consumers served. Trenchless technologies will help to reduce the conflicts with public transportation systems, but it must be realized such technologies also reduce the exposure of the public to the day to day needs and operations of the water distribution sector. Education and advertising aimed at the public must be encouraged, especially in overcoming the "conservation conundrum" where reduced demand through conservation will inevitably mean having to increase water rates to maintain revenues. Without continued funding from senior levels of government, increases in water rates over the long term could average as much as 41 percent over current levels.

Infrastructure funding as outlined by the Federal government's new $2 billion program is long overdue and very much required. But as evident in the public scepticism exhibited during the program's promotion throughout the election, there needs to be much more interaction and improved communication between public utilities and the people they serve. Ultimately, large funding programs, whether they come from federally or provincially collected taxes or locally collected water rates, must be administered to effectively solve specific problems rather than unconditionally distributed to where they could be inappropriately used to prop up general revenue funds or other discretionary uses at the hands of local officials. The recent infrastructure program announced by the federal government should base funding upon sound plans for the future by the local municipalities. Infrastructure assessments which rationally assess the system deficiencies and aim at effectively rectifying the problems must be promoted and could even be funded under the new program. These systems must be based on generally accepted and adopted standards of system condition and service. Investigations similar to the one outlined within Pitt Meadows must be carried out in even more detail in all communities across Canada. Communities which have been maintaining systems properly over the years should also be permitted to participate and receive an equitable share of the funding, to better develop their management techniques and technologies, or to assist in sharing their information and techniques with other communities.

Such information exchanges must be promoted. Federal and provincial agencies could assist in the continued collection and analysis of condition assessments through the development of standardized, user-friendly condition assessment programs, breakage reports, and decision costing programs. Guidelines for effective combination replacement/renovation programs should be developed and implemented over the next two to three years, perhaps in coordination with the new infrastructure program.

As a nation, we must recognize that the problems and solutions will vary across the country. The smaller, older communities of Atlantic Canada are in dire need of immediate upgrading of their deteriorating water systems. In Western Canada, where funds have typically been more available, especially in B.C. and Alberta, systems are relatively younger and in better condition. The program implemented must have a sufficiently long time frame which can address both the immediate and the future needs of these systems.

As with so many considerations in our nation, equity among regions must be maintained to enhance the national character, standards, and condition of all systems. This will mean appropriating of funds by the federal government based on need will have to be properly balanced by equity concerns among all regions. In any case, the importance of water infrastructure and indeed all infrastructure must be promoted for its inherent benefits, not just as excuses for "make-work" employment exercises. As such, research and policies for roads, sewers, storm systems, treatment facilities, and bridges should also be promoted at the national levels. Studies similar in purpose and content to this thesis, focusing on the unique character of Canadian systems, must also be promoted in the other component systems of our physical infrastructure. The standard of living and the fabric of our nation did not merely happen by accident and should not be allowed to diminish by accident. Rather than being taken for granted, infrastructure systems must be actively promoted and supported. All too often we forget the real need for effective, efficient, and safe infrastructure systems until a water main breaks - and we are thirsty.

BIBLIOGRAPHY

BIBLIOGRAPHY

Adams, B.J. and G.W. Heinke; 1987; "Canada's urban infrastructure: rehabilitation needs and approaches"; Canadian Journal of Civil Engineering; No. 14; 1987; pp. 700-707.

Alberta Municipal Affairs; 1943-1988; "Annual Report: Summary Municipal Statistics"; Department of Municipal Affairs; Government of Alberta; Edmonton, Alberta; 1943, 1946, 1950, 1951, 1956, 1958, 1961, 1966, 1971, 1981, 1986, 1988.

Alberta Environment; 1988; Standards and Guidelines for Municipal Water Supply, Wastewater, and Storm Drainage Facilities; Alberta Environment; Edmonton; March, 1988.

Allman, R.J. and J.D. Dilay; 1983; "Policies for Pipeline Safety Near Urban Areas"; Proceedings on the Conference on Pipelines in Adverse Environment II; Pipeline Division of the ASCE; San Diego, Calif.; Nov. 14-16; 1983; pp. 212 - 237.

Amborski, D. and E. Slack; 1987; "Federal, Provincial, Municipal Co-operation: Past, Present, and Future"; The Proceedings of the First Canadian Conference on Urban Infrastructure; Sodanell Canada Inc.; Edmonton, Alberta; February 5-6, 1987; pp. 37 - 52.

Anderson, J.D.; 1979; "The Municipal Government Reform Movement in Western Canada, 1880-1920"; Usable Urban Past: Planning and Politics in the Modern Canadian City; edited by F.J. Artibise and G.A. Stelter; MacMillan Company of Canada Limited in association with the Institute of Canadian Studies; Carleton University; Ottawa; 1979.

Anderson, L.; 1988; "Water Supply"; Building Canada: A History of Public Works; Norman R. Ball, Senior Editor; Canadian Public Works Association; University of Toronto Press; Toronto; 1988.

Andreaou, S. and D. Marks; 1987; "Maintenance Decisions for Deteriorating Water Pipelines"; Journal of Pipelines; Elsevier Science Publishers B.V., Amsterdam, The Netherlands; Vol. 7; 1987; pp. 21-31.

Arnold, G.E.; 1960; "Experience with main breaks in four large cities"; Journal of the American Water Works Association; 53(8); 1960; pp. 1041 - 1044.

Artibise, Alan F.J.; 1981; Town and City: Aspects of Western Canadian Urban Development; Canadian Plains Research Centre; University of Regina; Regina, Sask.; 1981.

ASCE; 1989; Reliability Analysis of Water Distribution Systems; Task Committee on Risk and Reliability Analysis of Water Distribution Systems of the Committee on Probabilistic Approaches to Hydraulics of the Hydraulics Division of the American Society of Civil Engineers; Edited by Larry W. Mays; American Society of Civil

Engineers; New York, New York; 1989; 532 p.

AWWA; 1974; "A Study of the Problem of Asbestos in Water"; AWWA Journal Part 2; American Water Works Association; Denver, Colorado; 1974.

AWWA; 1983; Manual of water supply practices: Water rates; American Water Works Association; M1; Denver, Colorado; 1983.

AWWA; 1986a; Guidance Manual: Water Main Evaluation for Rehabilitation / Replacement; Report prepared by D. Kelly O'Day; American Water Works Association; Denver, Colorado; 1986; 182 p.

AWWA; 1986b; "Are Asbestos Fibres in Drinking Water Harmful?"; AWWA Journal, 78, No. 111; American Water Works Association; Denver, Colorado; November, 1986; pp. 18-26.

AWWA; 1988; Bacterial Regrowth in Distribution Systems; Report prepared by W.G. Characklis; American Water Works Association; Denver, Colorado; January, 1988; 331 p.

AWWA; 1989; Economics of Internal Corrosion Control; American Water Works Association; Denver, Colorado; October, 1989.

B.C. Municipal Affairs; 1980; Residential Services and Site Planning Standards; Ministry of Municipal Affairs; Province of British Columbia; Victoria, B.C.; 1980.

B.C. Municipal Affairs; 1951-1988; Municipal Statistics; Ministry of Municipal Affairs; Province of British Columbia; Victoria, B.C.; 1951, 1952, 1953, 1955, 1956, 1958, 1966, 1971, 1975, 1976, 1981, 1982, 1985, 1986, 1988.

Baldwin, 1988; Building Canada: A History of Public Works; Norman R. Ball, Senior Editor; Canadian Public Works Association; University of Toronto Press; Toronto; 1988.

Barclay, D.S.; 1984; "Retrofitting apartment buildings to reduce costs and water demand"; Canadian Water Resources Journal; 9(3); 1984; pp. 45-47.

Birchan, P.D. and W.K. Bond; 1984; "The Impacts of Land Use on CMHC Municipal Infrastructure Assistance, 1961 to 1981"; Working Paper No. 32; Lands Directorate; Environment Canada; March, 1984.

Bloomfield, E., G. Bloomfield, and P. McKaskel; 1983; Urban Growth and Local Services: The Development of Ontario Municipalities to 1981; Occasional Papers in Geography No. 3; Dept. of Geography; University of Guelph; Guelph, Ont.; September, 1983.

Bradley, J.; 1987; "Political and Financial Challenges of Infrastructure Renewal; The Proceedings of the First Canadian Conference on Urban Infrastructure; Sodanell Canada Inc.; Edmonton, Alberta; February 5-6, 1987; pp. 31 - 35.

Bratton, George N.; 1990; Personal Interview; Water Works Engineer; City of Vancouver, B.C.; May 31, 1990.

Bratton, G.N., G.P. Duppong, and D.D. Green; 1986; "Planning of Watermain Replacement Using Time-To-Failure Analysis and Risk Assessment Techniques"; A Paper presented at the Conference of the Pacific Northwest Section of the American Water Works Association; Portland, Oregon; 1986.

Brooks, D.B., and R. Peters; 1988; "Water: The potential for demand management in Canada"; Discussion Paper; Science Council of Canada; Ottawa; 1988; as cited in Tate 1990.

Buelow, R.W., J.R. Millette, E.F. McFarren and J.M. Symons; 1980; "The Behavior of Asbestos-Cement Pipe Under Various Water Quality Conditions: A Progress Report"; AWWA Journal; Research and Technology; February, 1980; pp. 91-102.

Bury, K.; 1975; Statistical Models in Applied Science; John Wiley; New York; 1975.

Cain, L.P.; 1976; "Water and Sanitation Services in Vancouver: An Historical Perspective"; B.C. Studies; University of British Columbia Press; Vancouver, B.C.; No. 30; Summer 1976; pp. 27-43.

Canada World Almanac; 1990; The Canadian World Almanac and Book of Facts; Global Press; Canada Publishing Corporation; Toronto, Ontario; 1990; 691 p.

Canadian Geotechnical Society; 1985; Canadian Foundation Engineering Manual; 2nd Edition; Canadian Geothechnical Society; BiTech Publishers Ltd.; Vancouver, B.C.; 1985; 456 p.

Caproco; 1985; Underground Corrosion of Water Pipes in Canadian Cities Case: The City of Calgary; Final Report; Prepared by Caproco Corrosion Prevention Ltd.; Edmonton, Alberta; Published by Minister of Supply and Services Canada, Ottawa; 1985.

Careless, J.M.S.; 1978; The Rise of Canadian Cities in Canada before 1914; Canadian Historical Association; No. 32; Love Printing Services Ltd.; Ottawa; 1978.

CBA; 1981; Feasibility Study for Upgrading and Extending Water Supply in Pitt Meadows and Pitt Polder; Report No. 811; B.C. Ministry of Environment prepared by CBA Engineering Ltd.; Vancouver, B.C.; February, 1981.

City of Winnipeg; 1991; "DRAFT": Guidelines for Usage of Trenchless Methods for the Rehabilitation or Renewal of Sewer Infrastructures; City of Winnipeg, Works and Operations Division; Winnipeg, Manitoba; May, 1991; 10 p.

Chambers R.E. and T.J. McGrath; 1981; "Structural Design of Buried Plastic Pipe"; Proceedings of the First International Conference on Underground Plastic Pipe; Pipeline Division of the American Society of Civil Engineers; New Orleans, Louisiana; March

30 - April 1, 1981; pp. 10 - 25.

Clark, R.M., C.L. Stafford, and J.A. Goodrich; 1982; "Water Distribution Systems: A Spatial and Cost Evaluation"; Journal of the Water Resources Planning and Management Division; American Society of Civil Engineers; Vol. 108; No. WR3; October, 1982.

Clarke, N.W.B.; 1968; Buried Pipelines: A Manual of Structural Design and Installation; MacLaren and Sons Ltd.; London; 1968.

Commins, B.T.; 1979; Asbestos in Drinking Water; Water Research Centre Technical Report TR100; Medmenham Laboratory; Buckinghamshire, England; 1979.

Cotruvo, J.; 1984; "Contaminants in Drinking Water"; National Conference on Critical Issues in Drinking Water Quality; Federation of Associations on the Canadian Environment; Ottawa; Feb. 6 and 7; 1984.

Cross, Greg; 1991; Telephone Interview; Engineering Technologist; The Corporation of the District of Pitt Meadows, B.C.; July 24, 1991.

Curtis, W.H.; 1987; "State of Urban Infrastructure in Canada"; The Proceedings of the First Canadian Conference on Urban Infrastructure; Sodanell Canada Inc.; Edmonton, Alberta; February 5-6, 1987; pp. 1-16.

Curtis, W.H.; 1991a; Personal Interview; City Engineer, City of Vancouver; June 13, 1991.

Curtis, W.H.; 1991b; "Report to the Task Force on Municipal Infrastructure From Chairman of the Technical Committee on Infrastructure: Status of Municipal Infrastructure Renewal"; unpublished report; March 5, 1991.

Davey, T.; 1987; "Why Canadians can't afford cheap water"; Water and Pollution Control; Vol. 125; No. 5; October, 1987; p. 5.

Davis, M.J., B.L. Haerndon, E.P. Shea, and M.K. Snyder; 1979; "Occurrence, Economic Implications and Health Effects Associated with Aggressive Waters in Public Water Supply Systems"; Final Report, Midwest Research Institute Project No. 4552-L; Kansas City, Missouri; 1979.

deCamp, L. Sprague; 1990; The Ancient Engineers; Dorset Press; New York; 1990.

Denis, Leo G.; 1912; Water-Works of Canada; Commission of Conservation; Murtimer Co.; Ottawa; 1912.

Denis, Leo G.; 1916; Water Works and Sewerage Systems; Commission of Conservation; Ottawa; 1916; p.5.

DoE and NWC; 1977; Sewers and Water Mains - a National Assessment; DoE and

NWC Standing Technical Committee Report No. 4; NWC; London, England; 1977; 34 p.; as cited in Edwards and Cox 1982.

Doherty, D.C., N. Vardin, and C.S. Kitchen; 1987; "Upkeep of Municipal Services: The Toronto System"; The Proceedings of the First Canadian Conference on Urban Infrastructure; Sodanell Canada Inc.; Edmonton, Alberta; February 5-6, 1987; pp. 229-254.

Dunlop; 1983; Rebuilding America's Vital Public Facilities; Labour Management Group; Harvard University; 1983; as cited in FCM 1984.

Edwards, G. and G.C. Cox; 1982; "The renewal of urban water and sewerage systems"; Planning and the Civil Engineer; proceedings of a joint conference of the American Society of Civil Engineers, the Canadian Society for Civil Engineering and the Institution of Civil Engineers, held in Torquay, September 20-25, 1981; Thomas Telford Limited; London; 1982.

Environment Canada; 1975; Canada Water Year Book; Environment Canada; published by Information Canada; Ottawa; 1975.

Environment Canada; 1983; Canada Water Year Book: Water and the economy; Environment Canada; published by the Minister of Supply and Services Canada; Ottawa; 1983.

Environment Canada; 1986; Stopping Acid Rain ; Government of Canada, Department of the Environment; Ottawa; 1986; 5 p.

Environment Canada; 1987; Federal Water Policy; Government of Canada, Minister of the Environment; Ottawa; 1987; p. 21.

Environment Canada; 1990a; A Primer on Water: Questions and Answers; Environment Canada; Ottawa; 1990.

Environment Canada; 1990b; Federal Water Policy: A Progress Report; Interdepartmental Committee on Water; Government of Canada, Minister of the Environment; Ottawa; March, 1990; p. 32-35.

ERCB; 1983; An Analysis of Pipeline Performance in Alberta; Energy Resources Conservation Board; Calgary, Alberta; 1983.

ESE; 1991; "Corrosion control in Calgary's water distribution system"; Environmental Science and Engineering; July, 1991; pp. 44-46.

FACE; 1975; National Inventory of Municipal Waterworks and Wastewater Systems in Canada - 1975; Federation of Associations on the Canadian Environment and participating Federal and Provincial agencies; published by the Minister of Supply and Services Canada; Ottawa; 1975.

FACE; 1978; National Inventory of Municipal Waterworks and Wastewater Systems in Canada - 1977; Federation of Associations on the Canadian Environment and participating Federal and Provincial agencies; published by the Minister of Supply and Services Canada; Ottawa; 1978.

FACE; 1981; National Inventory of Municipal Waterworks and Wastewater Systems in Canada - 1981; Federation of Associations on the Canadian Environment and participating Federal and Provincial agencies; published by the Minister of Supply and Services Canada; Ottawa; 1981.

FACE; 1987; National Inventory of Municipal Waterworks and Wastewater Systems in Canada - 1986; Federation of Associations on the Canadian Environment and participating Federal and Provincial agencies; published by the Minister of Supply and Services Canada; Ottawa; 1987.

FCM; 1984; Canada's urban Infrastructure: Physical Condition and Funding Adequacy; a report prepared for the Federation of Canadian Municipalities Task Force on Municipal Infrastructure by the Technical Committee on Canada's Urban Infrastructure; Ottawa; June, 1984.

FCM; 1989; Defining Minimum Maintenance Standards for Infrastructure Feasibility Evaluation; a report prepared for the Federation of Canadian Municipalities Task Force on Municipal Infrastructure by the Technical Committee on Canada's Urban Infrastructure; Ottawa; September, 1989.

FCM; 1991a; "Impact of Infrastructure Improvement on the Environment, Public Health, and Safety"; unpublished report of the Federation of Canadian Municipalities Technical Committee on Canada's Urban Infrastructure; Ottawa; May 28, 1991.

FCM; 1991b; "Minutes of the Infrastructure Technical Meeting - Ottawa May 27, 1991"; unpublished minutes of the Federation of Canadian Municipalities Technical Committee on Canada's Urban Infrastructure; Ottawa; May 27, 1991.

Fedotoff, R., Frutchey, R. and Thomson, J; 1990; "Pipe Rehab: Old Notions Challenged"; WATER / Engineering & Management; April, 1990; pp. 24-27.

Flack, E.J.; 1981; "Residential water conservation"; Journal of Water Resources Planning Management Division of the ASCE; ASCE; Vol. 107; No. 1; 1981; p. 85-95.

FUS; 1981; Water Supply for Public Fire Protection: A Guide to Recommended Practice; Fire Underwriters Survey; Insurance Bureau of Canada; Toronto, Ontario; 1981; 24 p.

Graf, F.L.; 1989; "Locating Pipe and Piping Leaks Using Ground Penetrating Radar"; Proc. of the First International Conference on Underground Infrastructure Research; Nov. 15-17, 1988; AWWA; Denver; published 1989; pp. 61-72.

Grigg, N.S.; 1986; "Water Infrastructure: Research Needs and Education Needs"; Water Forum '86; World Water Issues in Evolution; Proceedings of the Conference Sponsored by the Hydraulics Division of the American Society of Civil Engineers; Vol. 2; Long Beach, California; Aug. 4-6, 1986.

Grigg, N.S.; 1988; Infrastructure Engineering and Management; John Wiley and Sons, Inc.; New York, New York; 1988; 380 p.

Grima, A.P.; 1972; Residential demand for water: alternative choices for management; University of Toronto Press; Toronto, Ontario; 1972; as cited in Tate 1989.

Grover, B. and D. Zussman; 1985; "Safeguarding Canadian Waters"; Inquiry on Federal Water Policy Research Paper No. 4; Environment Canada; Ottawa; March, 1985.

Grover, A.; 1990; "Speech to the Canadian Conference on Urban Infrastructure"; Proceedings of the Second Canadian Conference on Urban Infrastructure; February 13 and 14, 1989; Sodanell Canada Inc.; Edmonton, Alberta; 1990.

GVRD, 1990; Greater Vancouver Key Facts: A Statistical Profile of Greater Vancouver, Canada; GVRD Development Services; Burnaby, B.C.; 1990; 82 p.

Hall, R.; 1984; "The Quality of Existing Water Systems and Public Perception"; National Conference on Critical Issues in Drinking Water Quality; Federation of Associations on the Canadian Environment; Ottawa, Ontario; February 6 & 7, 1984; pp. 46-49.

Haney, P.E. and Hagar, P.E.; 1985; "Dual water system design"; AWWA Seminar proceedings - Dual water systems; No. 20189; Conference of the American Water Works Association; Denver, Colorado; June 23, 1985; as cited in Tate 1990.

Hanke, S.H.; 1978; "A method for integrating engineering and economic planning"; Journal of the American Water Works Association; AWWA; Vol. 70; No. 9; pp. 487-491; as cited in Tate 1990.

Health and Welfare Canada; 1989; Guidelines for Canadian Drinking Water Quality; Fourth Edition; Minister of National Health and Welfare; published by the Minister of Supply and Services Canada; Ottawa; 1989; 25 p.

Heinke, G.W. and E.J. Bowering; 1984; "Literature Review of municipal Infrastructure"; Appendix "A" of Canada's urban Infrastructure: Physical Condition and Funding Adequacy; a report prepared for the Federation of Canadian Municipalities Task Force on Municipal Infrastructure by the Technical Committee on Canada's Urban Infrastructure; Ottawa; June, 1984.

Hennigar, G.W.; 1984; "Water Leakage Control and Sonic Detection"; Canadian Water Resources Journal; Vol. 9; No. 3; 1984; pp.48-50.

Hickman, R.; 1984; "Hazards in Drinking Water"; National Conference on Critical Issues in Drinking Water Quality; Federation of Associations on the Canadian Environment; Ottawa, Ontario; February 6 & 7, 1984; pp. 91-98.

Howe, C.W. and F.P. Linaweaver, Jr.; 1967; "The impacts of price on residential water demand and its relation to system design and price structure"; Water Resour. Res.; 3(1); pp. 13-32; as cited in Tate 1989.

Hudson, W.R. and Haas R.; 1978; Pavement Management Systems; McGraw - Hill Book Company; New York; 1978.

Hunsinger R.B., D.B. Jobb, K.J. Roberts, P.J. Roberts, O.R. Lindow and J.F. Wainright; 1989; Asbestos in Ontario Drinking Water Supplies; Water Resources Branch and Laboratory Services Branch; Ontario Ministry of Environment; Queen's Printers for Ontario; 1989.

IBC; 1989; Facts: Facts of the General Insurance Industry in Canada; Insurance Bureau of Canada; Toronto; 1989.

IUCN; 1980; "World Conservation Strategy"; International Union for Conservation of Nature and Natural Resources; Gland, Switzerland; 1980; p. 1; as cited in Tate 1990.

James, B. and Nq, W.; 1991; "Corrosion control in Calgary's water distribution system"; Environmental Science & Engineering; July, 1991; pp. 44-46.

Kettler A.J. and I.C. Goulter; 1985; "An analysis of pipe breakage in urban water distribution networks"; Canadian Journal of Civil Engineering; 1985; pp. 286 - 293.

Lalani, Amin; 1990; Personal Interview; Water and Sewer Engineer; Municipality of Surrey, B.C.; June 21, 1990.

Loudon, R.M.; 1986; "Municipal experiences in pricing and water conservation"; A paper delivered at the Canadian Public Works Conference and Equipment Show; Ottawa, Ontario; May 11-14, 1986; as cited in Tate 1990.

Lowry, Jim; 1991; Personal Interview; Director of Engineering; The Corporation of the District of Pitt Meadows, B.C.; September 4, 1991.

MacLaren, J.W.; 1983; Report to the Ministry of the Environment of the Province of Ontario on a Water Distribution and Sewerage Rehabilitation Program for Ontario Municipalities; prepared by James W. MacLaren Consulting Engineer; Ontario Mimistry of the Emvironment; Toronto, Ontario; 1983.

MacLaren, J.W.; 1985; "Municipal Waterworks and Wastewater Systems"; Inquiry on Federal Water Policy Research Paper No. 3; Environment Canada; Ottawa; January, 1985.

MacLaren, J.W.; 1987; "Underground Piping Systems"; Proceedings of the First Canadian

Conference on Urban Infrastructure; Sodanell Canada Inc.; Edmonton, Alberta; February 5-6, 1987; pp. 137-152.

MacLaren, James W.; 1991; Telephone Interview; Technical Advisor, Ontario Water Services Secretariat; Toronto, Ontario; May 24, 1991.

MacLean, John; 1991; Telephone Interview; District of North Vancouver; Design Engineer/Supervisor; July 15, 1991.

Macleans; 1990; "Danger in the Water"; Macleans Magazine; Maclean Hunter Canadian Publishing; Toronto, Ontario; Vol. 103; No. 3; January, 1990; pp. 30-41.

Mannion, J.B.; 1988; "Health Effects of Drinking Water Contaminants"; Journal of the New England Water Works Association; Vol. 102; No. 2; March 1988; pp. 6-12.

Marks, D.H.; 1987; "Maintenance Management in Urban Water Distribution Infrastructure"; Third Canadian Seminar on systems Theory for the Civil Engineer"; Ecol. Polytech.; Montreal, Quebec; June 10, 1987.

Marks, D.H., S. Andreou, and R. Clark; 1986; "Guidelines for Maintenance of Aging Water Pipes"; Water Forum '86: World Water Issues in Solution; 1986; pp. 1225 - 1231.

Mavinic, Donald S.; 1990; Personal Interview; Professor of Civil Engineering; University of British Columbia; May 9, 1990.

Mays, L.W.; 1989; "Introduction"; Reliability Analysis of Water Distribution Systems; By the Task committee on Risk and reliability Analysis of Water Distribution Systems of the Committee on Probabilistic Approaches to Hydraulics of the Hydraulics Division of the American Society of Civil Engineers; American Society of Civil Engineers; New York, New York; 1989; pp. 1-10.

McClelland, N.I.; 1981; "Monitoring for Toxicological Safety"; International Conference on Underground Plastic Pipe; Sponsored by the Pipeline Division of the American Society of Civil Engineers; New Orleans, Louisiana; Mar. 20 - Apr. 1, 1981; pp. 401-419.

McColl, S.R.; 1985; "Risk Assessment and Standard-Setting for Control of Chemical Hazards in Canadian Drinking Water"; A paper prepared for the Risk Management Workshop; Inquiry on Federal Water Policy Research Paper #19; Environmental Protection Service; Environment Canada; Hull, P.Q.; June, 1985.

McIntyre, C.E. and J.C. Elstad; 1987; "A Rehabilitation Program for Water and Sewer Services in Ontario"; Proceedings of the First Canadian Conference on Urban Infrastructure; Sodanell Canada Inc.; Edmonton, Alberta; February 5-6, 1987; pp. 279-301.

Millette, L. and D.S. Mavinic; 1988; "Effect of pH adjustment on the internal corrosion rate of residential cast-iron and copper water distribution pipes"; Canadian Journal of

Civil Engineering; Vol. 15; Feb. 1988; pp. 79-90.

Montreal; 1979-1984; Annual Report: Ville de Montreal; Montreal; 1979, 1980, 1981, 1982, 1983, 1984.

Morris, R.E.; 1967;" Principal Causes and Remedies of Water Mian Breaks"; Journal of the American Water Works Association; 59(7); 1967; pp. 782 - 798.

Morrison, A.; 1984; "Is Canada's Drinking Water Safe?"; National Conference on Critical Issues in Drinking Water Quality; Federation of Associations on the Canadian Environment; Ottawa; Feb. 6 and 7, 1984.

Moruzzi, L.; 1987; "Reasons for Pipe Damage"; Water Supply; Vol. 5; No. 3/4; 1987; pp. SS16-1 to SS16-8.

Moser, A.P.; 1990; Buried Pipe Design; McGraw Hill, Inc.; New York, New York; 1990; 219 p.

MOT; 1973; Estimating the Depth of Pavement Frost and Thaw Penetrations; Ministry of Transportation, Canadian Air Transportation Administration, Construction Engineering and Architectural Branch, Engineering Design Division; Report No. CBED-6-266; Ottawa; February 1973; 26 p.

MU; 1961; "Statistical Summary of Waterworks Systems in Canada"; Municipal Utilities; J.P. Russell, Editor; Monetary Times Publications Ltd.; Toronto; February, 1961.

MU; 1951; "Statistical Summary of Waterworks Systems in Canada"; Municipal Utilities; J.P. Russell, Editor; Monetary Times Printing Co. of Canada Ltd.; Toronto; Vol. 89; No. 12; December, 1951.

MUD; 1990; "Municipal (Water) Use Database (MUD)"; File 89MUD.WK1; Water Planning and Management Branch, Inland Waters Directorate, Environment Canada; Ottawa, Ontario; April 5, 1990.

Nebesar, B. and G.W. Riley; 1984; Asbestos/Cement Pipe Corrosion Part 1 - Historical, Technological, Economic and Statistical Background; Canadian Centre for Mineral and Energy Technology; Energy, Mines and Resources Canada; Minister of Supply and Services Canada; Ottawa; October 1984.

Nova Scotia Municipal Affairs; 1965-1988; Annual Report of Municipal Statistics; Department of Municipal Affairs; Government of Nova Scotia; Halifax, Nova Scotia; 1965, 1971, 1977, 1986, 1988.

O'Day, K.D.; 1983; "Analyzing Infrastructure Condition - A Practical Approach"; Civil Engineering; American Society of Civil Engineers; April, 1983; pp. 39-42.

O'Day, K.D.; 1984; "Aging Water Supply Systems: Repair or Replace?"; Infrastructure:

Maintenance and Repair of Public Works; Annals of the new York Academy of Science; New York, New York; December 5, 1984; pp. 241-258.

Ontario Municipal Statistics; 1934-1967; Annual Report of Municipal Statistics; Department of Municipal Affairs; Government of Ontario; Toronto, Ontario; 1934, 1941, 1942, 1951, 1961,1967.

Parker, M.E. and E.G. Peattie; 1984; Pipe Line Corrosion and Cathodic Protection; Gulf Publishing Company; Houston, Texas; 1984; 166 p.

Philips, M.R., F. Wu, D. Maudie, and T. Field; 1991; "Management of Urban Drainage: Challenges and Trends"; Proceedings of the Second Canadian Conference on Urban Infrastructure; Edmonton, Alberta, Feb. 13 and 14, 1989; Sodanell Canada Inc.; Edmonton, Alberta; 1991.

Postel, S.; 1985; "Conserving water: The untapped alternative"; Paper 67; Worldwatch Institute; Washington, D.C.; 1985; as cited in Tate 1990.

Price, R.E. and S.M. Wolf; 1989; "Non-Destructive Evaluations of Pipelines"; Proc. of the First International Conference on Underground Infrastructure Research; Nov. 15-17, 1988; AWWA; Denver; published 1989; pp. 73-104.

Robinson, J.E.; 1980; "Demand modification as a supply alternative: A case study of the Regional Municipality of Waterloo, Ontario, Canada"; Department of Environmental Studies; University of Waterloo, Waterloo, Ontario; Unpublished ms as cited in Tate 1990; 1980.

Robinson, Bill; 1991; Municipality of Burnaby; Public Works Superintendent; Telephone Interview; June 26, 1991.

Rodi, S.; 1987; "Infrastructure Management: A Geographic Information System Application"; Proceedings of the First Canadian Conference on Urban Infrastructure; Sodanell Canada Inc.; Edmonton, Alberta; February 5-6, 1987; pp. 99 - 106.

Ryder, R.A.; 1989; "Corrosion of Underground Services"; Proc. of the First International Conference on Underground Infrastructure Research; Nov. 15-17, 1988; AWWA; Denver; published 1989; pp. 147-158.

SCC; 1989; "Laurentide Motels v. Beauport (City)"; Supreme Court of Canada Decision; L'Heureux-Dube Judge; 1 R.C.S.; April 20, 1989.

Shamir, U. and D.D. Howard; 1979; "An Analytic Approach to Scheduling Pipe Replacement"; Journal of the American Water Works Association; AWWA; May 1979; pp. 248-258.

Shilts, W.W.; 1981; Sensitivity of Bedrock to Acid Precipitation: Modification by Glacial Processes; Geological Survey of Canada; Government of Canada; Ottawa; Paper 81-14;

1981; 7 p.

Smith, H.W.; 1989; Corrosion Management in Water Supply Systems; Van Nostrand Reinhold; New York, New York; 1989; 125 p.

Smith, J.Grove; 1918; Fire Waste in Canada; Commission of Conservation; Ottawa; 1918; p. 216-217.

Somers, E.; 1984; "The Risk from Drinking Water"; National Conference on Critical Issues in Drinking Water Quality; Federation of Associations on the Canadian Environment; Ottawa; Feb. 6 and 7, 1984.

Stein, D., K. Mollers and R. Bielecki; 1989; Microtunnelling: Installation and Renewal of Nonman - Size Supply and Sewage Lines by the Trenchless Construction Method; Ernst & Sohn Verlag fur Architektur und technische Wissenschaften; Berlin, Germany; 1989; 352 p.

Stephenson, D.; 1989; Pipeline Design for Water Engineers (Third Revised and Updated Edition; Elsevier Science Publishing Company Inc.; New York, New York; 1989; 263 p.

Surrey; 1978; Waterworks Manual; District of Surrey, B.C.; Surrey Engineering Department; March 1978.

Tate, D.M.; 1990; Water Demand Management in Canada: A State-of-the-Art Review; Inland Waters Directorate, Water Planning and Management Branch, Environment Canada; Ottawa; Social Sciences Series No. 23; 1990; 52 p.

Tate, D.M. and D.M. Lacelle 1987; Municipal Water Use in Canada; Water Planning and Management Branch; Inland Waters/Lands Directorate; Environment Canada; Ottawa; Social Sciences Series No. 20; 1987.

Tate, D.M.; 1989; Municipal Water Rates in Canada, 1986 - Current Practices and Prices; Inland Waters Directorate, Water Planning and Management Branch, Environment Canada; Ottawa; Social Sciences Series No. 21; 1989; 16 p.

Toft, P. and M.E. Meek; 1983; "Asbestos in Drinking Water: A Canadian View"; Environmental Health Perspectives; Vol. 53., pp. 177-180; March, 1983.

Toronto; 1971; Annual Report; City of Toronto; 1971.

Vagt, G.O.; 1980; "Asbestos"; Canadian Minerals Yearbook 1980; Energy, Mines and Resources Canada; published by the Minister of Supply and Service Canada; Ottawa; 1980.

Vardin, N.; 1991; "Keele Street Microtunnelling Project - Toronto, Ontario"; Unpublished paper by Nicholas Vardin, P.Eng., City Engineer and Commissioner of Public Works and the Environment, City of Toronto; Toronto, Ontario; May 23, 1991.

Vernooy, B. and Jordan, S.; 1983; "An Inside Look at the Pipeline"; Proceedings on the Conference on Pipelines in Adverse Environment II; Pipeline Division of the ASCE; San Diego, Calif.; Nov. 14-16, 1983; pp. 397-414.

Versanne, D.; 1987; "Causes of Water Main Damage"; Water Supply; Vol. 5; No. 3/4; 1987; pp. SS16-8 to SS16-12.

Walski, T.M.; 1982; "Economic Analysis of Rehabilitation of Water Mains"; Journal of the Water Resources Planning and Management Division; American Society of Civil Engineers; 108(WR3); October 1982; pp. 296 308.

Wareham, D.G. and E.A. McBean; 1985; "Assessment of Municipal Practices of Communities with Respect to Fireflow Guidelines"; Canadian Water Resources Journal; Vol. 10; No. 3; 1985; pp. 14-26.

Wilging, R.C.; 1981; "Plastics in Piping"; Proceedings of the International Conference on Underground Plastic Pipe; Sponsored by the Pipeline Division of the American Society of Civil Engineers; New Orleans, Louisiana; March 30 - April 1, 1981; pp. 1-9.

Williams, H.G.; 1987; "Legislation Needed to Rehabilitate Our Water and Sewer Infrastructure"; Infrastructure: Maintenance and Repair of Public Works; Annals of the New York Academy of Sciences; v. 431; New York; 1984; pp. 82 - 85.

Winnipeg; 1971-1986; Annual Financial Report; City of Winnipeg; 1971, 1976, 1981, 1986.

Wilging, R.C.; 1981; "Plastics in Piping"; Proceedings of the International Conference on Underground Plastic Pipe; Sponsored by the Pipeline Division of the American Society of Civil Engineers; New Orleans, Louisiana; March 30 - April 1, 1981; pp. 1-9.

Wilging, R.C.; 1981; "Plastics in Piping"; Proceedings of the International Conference on Underground Plastic Pipe; Sponsored by the Pipeline Division of the American Society of Civil Engineers; New Orleans, Louisiana; March 30 - April 1, 1981; pp. 1-9.

Winnipeg; 1931-1966; Report of the Commissioner of Finance; City of Winnipeg; 1931, 1932, 1936, 1941, 1946, 1951, 1956, 1961, 1966.

Wood, D.; 1987;"Urban Infrastructure: Municipal Liability"; Proceedings of the First Canadian Conference on Urban Infrastructure; Sodanell Canada Inc.; Edmonton, Alberta; February 5-6, 1987; pp. 185-197.

Young, O.C. and J.J. Trott; 1984; Buried Rigid Pipes: Structural Design of Pipelines; Elsevier Applied Science Publishers Ltd.; Essex, England; 1984; 234 p.

APPENDIX A

APPENDIX A: DATA SOURCES FOR THE NATIONAL INVENTORY

A.1. Database Information

The lack of a comprehensive inventory of Canada's underground plant has been noted by a variety of sources (Tupper 1981, FCM 1984, MacLaren 1985) and to date no agency keeps such records on a national scale.

Although a variety of information exists within individual municipalities in some form or another, no agency has yet to compile a comprehensive data base, although the 1984 FCM survey was a first step (FCM 1984). In England a comprehensive survey was carried out in 1977, from which courses of action could be taken (DoE and NWC 1977).

Historical data from provincial municipal statistics reports, trade journals, annual reports of various cities, and past system surveys is used to estimate the amount of pipe beneath Canada's villages, towns, and cities (see Table A.1).

Table A.1: Data Sources Used in Estimating the Canadian Water Pipes Inventory

SOURCE	EXTENT	COMMUNITIES	DATA INCLUDED	YEARS
Denis 1912	National	all	Population; Pipe length, type, size range	1912
Municipal Utilities 1951	National	pop. > 1,000	Population; Pipe length, type, size range	1951
Municipal Utilities 1961	National	pop. > 1,000	Population; Pipe length, type, size range	1961
Provincial Municipal	B.C.	all	Population; Pipe Length	1951-1988
Statistics Reports	Alberta	all	Population; Pipe Length	1943-1988
(Years Vary)	Ontario	all	Population; Pipe Length	1934-1967
	Nova Scotia	all	Population; Pipe Length	1965-1988
Annual Reports	Winnipeg	n/a	Pipe Length	1932-1986
(Years Vary)	Montreal	n/a	Pipe Length	1979-1984
	Toronto	n/a	Pipe Length	1971
FCM 1984 (survey data)	National	limited	Pipe Length	1984
FACE 1975	National	all	Population Served; Number of Systems	1975
FACE 1978	National	all	Population Served; Number of Systems	1977
FACE 1987	National	all	Population Served; Number of Systems	1986

Unfortunately none of the sources are ideal, neither individually nor when combined. There remains major gaps in the data, but what does exist is still very useful in forming an initial picture of what for now cannot be seen below our streets.

One of the earliest comprehensive surveys of Canada's piped water systems was carried out by the Federal Government's Commission of Conservation in 1912 (Denis 1912). On a community by community basis, this listing provides information on pipe lengths by the material type and the minimum to maximum pipe diameter range in a system. The survey also includes information on the population served, the ownership, the nature of the supply source (ie lake or river), the operating pressure, the consumption, the number and capacity of storage reservoirs, as well as a count of the valves, services, and hydrants on the each community's system.

Two surveys of a similar format were carried out by Municipal Utilities in 1951 and 1961, but the sample was limited to communities of at least 1,000 in population. Later surveys carried out by the publication did not include information specific to the distribution system such as pipe length and type.

Additional information which is useful in the estimation of pipe length has been extracted from various provincial municipal statistics publications which are typically put out by the provincial ministry or department responsible for municipal affairs. Although these publications are primarily summaries of the fiscal situation of individual municipalities, some provinces include information on the length of public services such as roads, sewers, and water mains. Unfortunately, the format of each publication and the information gathered varies both from year to year and from province to province (see Table A.1). Both historical and current statistics for British Columbia, Alberta, and Nova Scotia were obtained from these records, while the Ontario reports were only available up to 1967 and thus proved to be much less useful. Provinces such as Saskatchewan, Manitoba, Quebec, New Brunswick, Newfoundland, and Prince Edward Island do not publish such statistics in a readily available publication.

The annual report of larger cities Winnipeg and Montreal are used to obtain recent estimates of system length. Unfortunately, only large centres publish and widely distribute such reports, thus limiting their usefulness as an accessible source.

Pipe length data from the FCM survey in 1984 has been obtained for an additional 14 municipalities in Canada and estimated for 1986. The municipalities are all in the large or medium sized category and are all located outside of the three provinces of B.C., Alberta, and Nova Scotia. A few of the municipalities included are Toronto, North York, York, Sault Ste. Marie, London, Quebec City, Fredericton, and Regina.

The final source which is used in the 1986 estimate of pipe length in Canada is the National Inventory of Municipal Waterworks and Wastewater Systems in Canada 1986 (FACE 1986) which provides the most comprehensive and current information on the number of communities in Canada with water distribution systems and the corresponding populations served. Two similar documents (FACE 1975, FACE 1978) which were published earlier are not used extensively in this report.

A.2. Methodology

The data is stored in a spreadsheet program, having been transferred from the various publications by the author. Heinke and Bowering (1984) estimate that in 1981 there were 100,000 km of water main in Canada based on a served population of 20,275,786 (FACE 1981) and an average density of 200 persons per kilometer of watermain, a value extracted from an Ontario Department of the Environment report (MacLaren 1983).

A.2.1. Missing Data

Nationally, the data available gives a very accurate total system length for 1912, a reasonably accurate length for both 1951 and 1961, and a reasonably good approximation of the length in 1986. The 1912 data (Denis 1912) is the only comprehensive account of Canadian systems (see Table 3.2) but there is still some missing data. The 1951 and 1961 data are more incomplete with respect to missing data, both within the surveyed communities and for communities less than 1,000 in population. For these three data sets, where population data is missing, appropriate census information is used. Where system length data is missing in a surveyed community, the length is approximated by applying the average population density per unit of water main from communities of similar size (ie in the same population interval) to the population of the community.

For the 1951 and 1961 data sets, the population in the communities under 1,000 in population is approximated by multiplying the number of communities by an assumed average population of 500; the pipe length is approximated by dividing the resulting population by the average population density per unit length of main for communities under 2500 in population for each respective year.

Table A.2: Canadian Water Main Inventory Data

	1912		1951		1961		1986	
	Pop.	Pipe	Pop.	Pipe	Pop.	Pipe	Pop.	Pipe
Systems with Complete Information	334	335	609	609	770	770	2887	658
Systems with Missing Information	11	10	103	103	118	118	-	2229
Systems with Missing Information (pop. < 1000)	-	-	753	753	990	990	-	-
Total Systems	346	346	1465	1465	1878	1878	2887	2887
Source	Denis 1912		MU 1951		MU 1961		Ab. Mun. Stats. 1986 B.C. Mun. Stats. 1986 N.S. Mun. Stats. 1986 FACE 1987 Misc. Annual Reports	

For the 1986 estimate of main length in Canada, population densities per unit length of pipe are calculated for the same population intervals as are used in the National Inventory of Municipal Waterworks and Wastewater Systems in Canada 1986 (FACE 1987) using five main sources: the 1986 Alberta Municipal Statistics (Alberta Municipal Affairs 1986), the 1986 B.C. Municipal Statistics (B.C. Municipal Affairs 1986), the 1986 Nova Scotia Municipal Statistics, the FCM (1984) survey data, and annual reports of Winnipeg and Montreal (Winnipeg 1984, Montreal 1984). The ten population intervals for which average population per unit length of pipe are calculated include:

1) greater than 1,000,000
2) 500,001-1,000,000
3) 250,001-500,000
4) 100,001-250,000
5) 30,001-100,000
6) 10,001-30,000
7) 5,001-10,000
8) 2,501-5,000
9) 1,001-2,500
10) less than or equal to 1,000

For each interval, an average population density per unit length of pipe is calculated and applied to the "population served" information provided by the national inventory (FACE 1987) to get total provincial and national values of main length.

The five sources represent 8,672,603 persons served, or 40 percent of the 21.4 million Canadians served by water distribution systems in Canada (FACE 1987). With such a significant sample size, the data is assumed to be representative of the remaining systems in Canada.

To calculate the most recent estimate of both the current total length of systems in Canada and the current population served, the national values estimated for 1986 are extrapolated linearly to 1991 using average growth values from 1986 to 1988 which are available for B.C. and Alberta, average growth values from 1977 to 1986 which are available for Nova Scotia, and some judgement on the part of the author for the other provinces.