Deterioration And Condition Rating Analysis Of Water Mains

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ABSTRACT

DETERIORATION AND CONDITION RATING ANALYSIS OF WATER MAINS

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In major cities world wide, deterioration of water mains is a continuous process; therefore, the need to improve the condition of water mains becomes crucial. While most municipalities have taken proactive measures in repairing, rehabilitating and replacing deteriorated water mains, more investigation still needs to be done in order to assist municipalities to make right decisions on limited budgets. Building deterioration models and prioritizing water main rehabilitation are more important than ever.

The deterioration of water mains includes structural and functional degradations. The present research focuses on the collection of water main data from municipalities and the analysis of water main breaks as a representative of the structural deterioration. Data have been collected from three municipalities that have large water distribution networks in Canada with a total water main length of 2,552 Km. Five multiple regression models have been developed, which show robust statistical analysis and are able to predict the annual break rates of individual water mains. They have been validated with reasonably satisfactory results. The developed models can be used for economical analysis of water

mains. However, the present research has found the limitations of the annual break rates in partially representing the individual water mains' conditions. The present research also studies the existing condition rating practices for prioritizing water mains. Finally, a preliminary condition rating scale on the structural deterioration of water mains has been proposed.

The methodology presented in the present research can be used in assisting municipalities to improve their decision making processes on water main asset management. The developed models as well as the condition rating approach suggested can help municipalities better interpret the conditions of their water mains and thus plan cost-effective investment to guarantee the acceptable level of services.

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Last and certainly not least, I wish to dedicate this thesis to my parents for their unconditional love and to my son, Eric, and daughter, Kiely, for the joy they have brought along to my family.

To you all, I dedicate this thesis.

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ABBREVIATIONS

AIP	Average Invalidity Percent
AVP	Average Validity Percent
ASCE	American Society of Civil Engineers
AWWA	American Water Works Association
AWWARF	American Water Works Association Research Foundation
AWWSC	American Water Works Service Co., Inc
C3	Chlorine Chemistry Council
CI	Cast Iron
CSCE	Canadian Society for Civil Engineers
DI-L	Ductile Iron (Lined)
DI-NL	Ductile Iron (Not Lined)
EPA	U.S. Environmental Protection Agency
GCI	Grey Cast Iron
GIS	Geographic Information System
GITA	Geospatial Information Technology Association
Hy	Hyprescon
IRC	Institute for Research in Construction, Canada
NRC	National Research Council, Canada
NZWWA	New Zealand Water and Wastewater Association
OFWAT	Office of Water Services, U.K.
OMWA	Ontario Municipal Water Association, Canada
PVC	Polyvinyl Chloride

CHAPTER 1

INTRODUCTION

1.1 General

Water mains are in poor condition and are deteriorating rapidly in major cities around the world. Since almost all water mains are buried underground, their conditions are difficult to assess. Most municipalities lack a mechanism to manage these buried assets in a way that can maximize their service lives while ensuring acceptable level of services. In recent years, much research has gone into this area in Canada, the U.S., Europe, New Zealand, and Australia. Municipalities are in great need of proper tools to assess the conditions of their water mains and to prioritize repair, rehabilitation and replacement decisions of their water main assets.

1.2 Research Objectives

The present research focuses primarily on the study of deterioration and aging of water mains including factors influencing their deterioration, deterioration models, and condition rating. The objectives of this research are as follows:

1) Collect and analyze water main data.
2) Study the existing deterioration models and check their validity to represent collected data.
3) Develop new deterioration models based on available municipal data.
4) Study current condition rating practices of water mains.
5) Propose a condition rating scale for water main structural deterioration.

1.3 Research Methodology

The methodology adopted in the present research is based on an intensive literature review of the deterioration and condition rating of water mains, and on the analysis of actual data collected from three municipalities in Canada, two of which are in Quebec, and one of which is in New Brunswick. The total length of the three networks is 2,552 Km. The analysis includes the following:

1) Review collected water main data to analyze break records and pipe network characteristics.
2) Perform descriptive statistical analysis of the collected data on water mains.
3) Review literature focusing on deterioration models, factors affecting water main deterioration, and condition rating practices.
4) Apply the existing deterioration models to the analyzed data.
5) Develop new deterioration models using regression analysis and perform their validation.
6) Perform sensitivity analysis to check the developed models' sensitivity to changes in the inputs.
7) Propose a preliminary condition rating scale based on water main breaks.
8) Discuss future research on water mains.

1.4 Thesis Organization

Chapter 2 presents a literature review comprising: 1) needs for water main research, 2) factors affecting the deterioration of water mains, 3) existing statistical deterioration models, 4) condition rating practices in municipalities, 5) statistics used for regression modeling, and 6) GIS practices in water main asset management. Different factors that influence the aging of water mains and the existing statistical models are described. The review of current condition rating for prioritizing water mains, GIS applications, and statistical techniques for developing regression modeling is presented.

Chapter 3 discusses the research methodology utilized in conducting the research work presented in this thesis, leading to the development of the deterioration models presented in Chapter 5.

Chapter 4 describes data collection and analysis process. A detail description of data collection, retrieval, analysis and filtering is presented. The descriptive statistics of water main data and the results of organizations and preliminary analysis of applicable data are presented.

Chapter 5 applies existing models on collected data and proposes new deterioration models. The unsatisfactory results of existing models application are presented. New models are validated and sensitivity analysis is implemented. Statistics related to the proposed deterioration models are described. Limitations of the developed models are summarized. A condition rating scale for water main structural deterioration is also proposed.

Chapter 6 provides concluding remarks and recommendations for future work.

CHAPTER 2

LITERATURE REVIEW

2.1 General

Water main deterioration has been gaining more attention than ever in the past two decades. Much research has been done to assess the existing condition of water mains and to promote the use of best infrastructure management systems and tools for water main life cycle analysis. The present research focuses on literature review of water main deterioration, models, prioritizing, and techniques about regression modeling.

Figure 2-1 shows a structure that contains the components discussed further in the literature review. It includes the factors that affect water main deterioration, existing deterioration models, applications of geographical information system in water main management, current condition rating practices, and statistical knowledge related to regression modeling.

2.2 Current Water Main Research Needs

In the U.S., the American Water Works Association (AWWA), the American Society of Civil Engineers (ASCE), and the Environmental Protection Agency (EPA), and in Canada, the National Research Council (NRC), as well as many other organizations world wide, have published significant research work on water mains and / or developed commercial asset management systems. Literature covers several topics, which include life cycle of water mains, performance evaluation and assessment, deterioration monitoring and forecasting, rehabilitation techniques, and decision making tools. Much more research is underway.

In Canada, the Committee for InfraGuide was created in 2001 with the co-operation of Infrastructure Canada, the Federation of Canadian Municipalities, NRC and the Canadian Public Work Association in order to develop and promote the use of best practices regarding municipal infrastructures including water mains. So far, many best practices have been adopted by municipalities in Canada and the Committee is still putting more efforts into the development of new best practices.

There is also a strong market drive that has boosted water main research and capital investment. It has been estimated, for example, that the cost of replacing all water mains in the U.S. could be as much as US$348 billion; to simply upgrade the water transmission and distribution systems would cost US$77 billion over the next 20 years. In Canada, the upgrades may cost about CAN$11.5 billion for only water mains (Baer, 1998).

2.3 Factors Influencing Deterioration of Water Mains

Unanticipated leaks and breaks due to deterioration of water mains can cause the loss of potable water, water contamination, flooding, real estate damage, and service interruptions to end users. They even pose a potential danger if they temporarily disable fire fighting capabilities. In extreme cases, people lost lives (Craun and Calderon, 2001). A severe break cost as much as US$2 million just for an emergency repair, without associating other impacts (Fortner, 1999).

In many municipalities, there may be pipes more than 100 years old that are still in operation. However, metallic pipes that are in their early ages may require immediate replacement due to a variety causes, for example, very corrosive soil. Kleiner and Rajani (2001a&b) have classified the deterioration of water mains into two categories: structural deterioration that reduces the ability of pipes to withstand various stresses, and deterioration of inner surfaces that reduces their hydraulic capacity and degrades water quality. In cases of severe internal corrosion, the deterioration of inner surfaces can cause structural deterioration as well.

According to Stone et al. (2002), researchers have studied many factors that contribute to the deterioration of water pipes, with the goal of developing or improving predictive planning models. As there are many factors that affect pipe failures and influence maintenance decisions, it is a very complex process to develop such models so as to assess all these factors. The factors affecting pipe deterioration can be either time-dependent or static. Those factors that will not change over time are static factors, such as pipe diameter or pipe material. On the other hand, pipe age, water pressure and temperature, soil corrositivity, temperature and water contents of soil, and previous pipe breaks are examples of

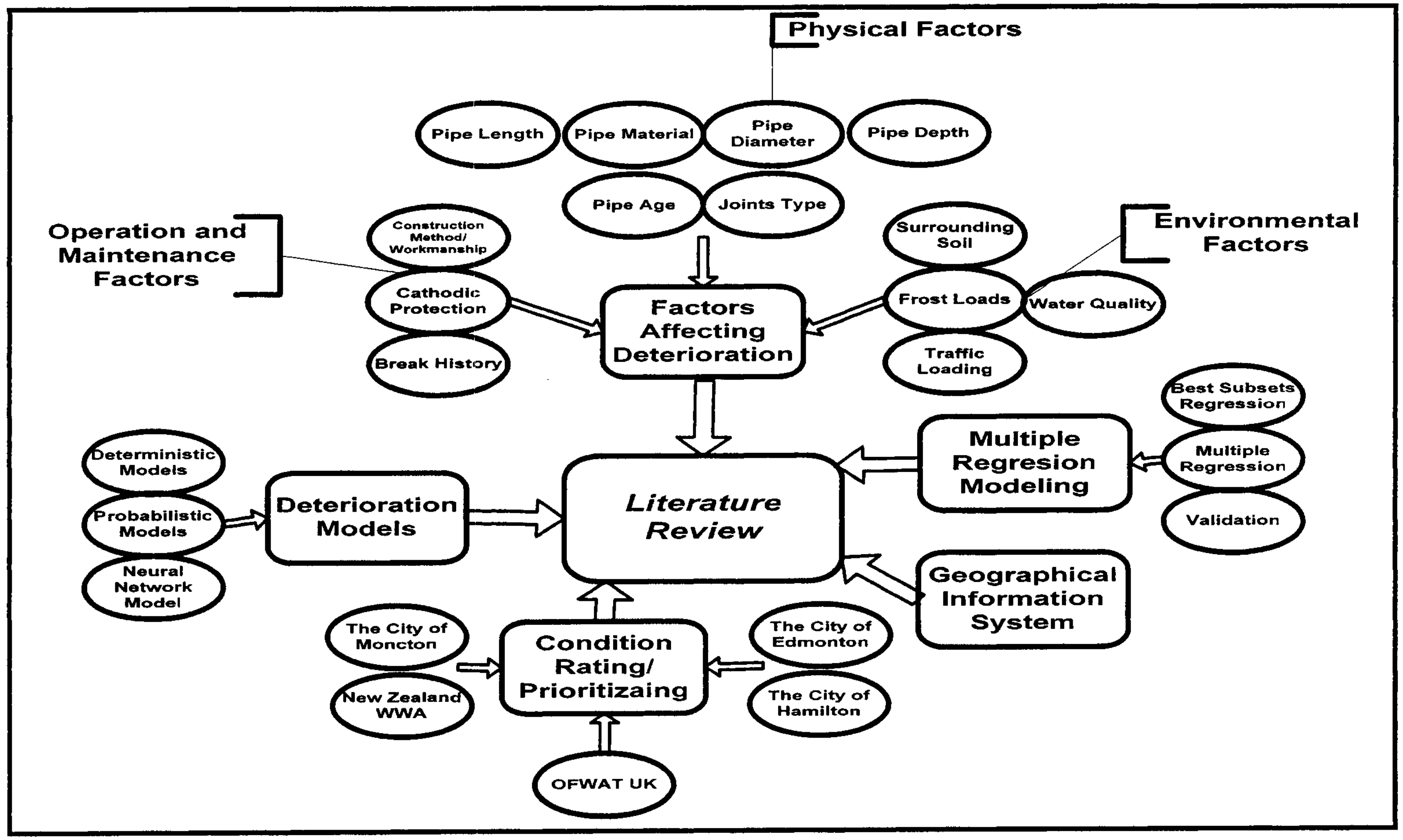

Figure 2-1 Literature Review Structure

random and time dependent factors. In other words, these factors can also be categorized as follows (Shamir and Howard 1979):

1) The quality and age of the pipe, including pipe material, diameter, length of pipe, and joints type.
2) The environment and climates where the pipe is exposed, such as the soil corrositivity, frost depth, soil temperature, soil moisture content, traffic and other loading.
3) The quality of workmanship when a pipe is installed, repaired, or rehabilitated, such as construction method (e.g., fill type).
4) The operating and maintenance factors of the pipe network, such as pressure and water hammer, pipe break and repair records and details, preventative maintenance (inspection, coating, cleaning, and cathodic protection for metallic pipes).

The factors given above all interact with one another when affecting the deterioration of a pipe both internally and externally. Many of these causal factors have been studied. As far as deterioration models are concerned, Kleiner and Rajani (2001a&b) have mentioned that no model exists that can explicitly and quantitatively consider all factors.

Pipe Material

Different materials have different characteristics and show different behaviors because of certain factors such as corrosion. In the deterioration analysis of water mains, pipe material is often used as the most important grouping criteria. American Water Works Service Co., Inc (AWWSC,2002) has summarized that cast iron pipes were predominantly in use before the 1940's and become less used after the 1970's, while ductile iron, PVC, and concrete pipes become more popular.

Pipe Diameter

It has been found that the deterioration of larger diameter pipes is slower compared to that of smaller diameter pipes in general according to several studies, such as Andreou and Marks (1986), and Walski et al. (1986). Kettler and Goutler (1985) have found a strong correlation between the pipe break rate and pipe diameter for cast iron pipes but not for asbestos cement pipes. Though the reasons for the decreasing tendency for breakage with increasing pipe diameter have not been completely understood, considerable evidence indicates that the inverse relationship may result from the greater pipe wall thickness of larger diameter pipes (Kettler and Goulter, 1985). On the other hand, larger diameter pipes can have a larger surface area in contact with surrounding soil, thereby resulting in an increased corrosion of the pipe.

Pipe Length

In general, the longer a pipe is, the more breaks may occur. This may be because the longer the pipe, the more conditions that it is exposed to. The increased number of conditions may stimulate breakage. There are various conditions that must be taken into account: poor surrounding fill, ground movement due to traffic loading, and underground water tables. On the other hand, longer pipe lengths can often be resulted from pipes runs in rural area where conditions are relatively uniform, while the use of shorter pipe lengths is often the case in urban areas with more complex conditions, which may increase their break rates. Also the longer a pipe is, the more connections it has, and thus the chance is greater that the pipe might fail (Skipworth et al., 2002).

Joints Type

Pipes of different materials may require different types of joints. Kettler and Goutler (1985) have cited the number of pipe failures for cast iron pipes installed between 1950 and 1959, from the 16^{th} to the 23^{rd} winter seasons after the end of the installation period. The failures of bolted and universal joints accounted for more than 70% (1226 out of 1686) of the total failures. In this same research, it was mentioned that it is typical for a joint failure in the City of Winnipeg to occur as a result of corrosion of the bolts used in the connections. These bolts in the soil of Winnipeg may be destroyed in only ten years. A detailed study on pipe failure due to types of joints to different pipe materials and to different pipe sizes has, to the best of my knowledge, still to be done.

Pipe Age

As we all know, as a pipe gets older, it may require more maintenance and repairs. Many rehabilitation plans have been based solely on the age of the pipes. Pascal and Revol (1994) have reported that the number of breaks in cast iron pipes increased with age. However, researchers have also suggested that age alone may not be a sufficient indicator for deciding when a pipe needs rehabilitation or replacement (O'Day 1982, Herbert 1994).

Kleiner and Rajani (2001a) have cited Kettler and Goutler's finding (1985) that the number of breaks per year is in linear relationship to pipe age. My careful study of the original paper reveals that Kettler and Goutler (1985) specifically used "winter seasons" rather than "pipe age" as the dependent variable for a set group of pipes installed in the 1950s. Thus the number of breaks is not really related linearly to the age of the pipes. Rather, the number of breaks per year is found proportional to the number of winter seasons after the end of the period of installation of this group of pipes in the City of Winnipeg.

Surrounding Soil (Corrositivity, Temperature and Moisture Content)

Corrosive soils can be the primary factor affecting a metallic pipe and leading to its structural deterioration. This external corrosion occurs mainly due to electrochemical reactions. There are four common types of such reactions: uniform, localized, galvanic, and concentration cell corrosion, according to American Water Works Association Research Foundation (AWWARF, 1996). O'Day (1989) has identified galvanic corrosion to be the main cause of external corrosion of iron water mains. Unlike iron mains, cement based pipes suffer mainly from degeneration chemical reactions rather than electrochemical reactions (AWWARF, 1996). This reaction results in leaching of CaO, a binding element in cement. Greek (1997) has cited an estimate that a quarter of the water pipe network in the U.K. was laid in highly aggressive and /or shrinkable soil. Strong evidence has showed that pipe breaks were caused by corrosion and fracture correlated with soil conditions. Jarvis and Hedges (1994) have concluded that soil corrositivity maps provided a sound basis for partitioning pipes into areas of different corrosion risk. Grau (1991) has also reported the use of soil maps for identifying high break rate areas. Researchers have also noted that the number of breaks tends to increase in winter seasons. One possible reason is that during cold seasons, the pipes tend to contract, thereby building up tension. Those pipes with flaws or defects are much weaker in tension, thereby causing more breaks (NRC,1996; Isenor and Lalonde, 2003)

C3 (1998) has stated that changes in soil texture, temperature, moisture, oxygen, chemical make-up, organic material and bacteria are among the common factors that can cause corrosion pipe failure. The officials from Florida to Ontario have reported that ground conditions affect aging pipelines. It also has mentioned that drought periods followed by heavy rain may cause ground conditions to become unstable, resulting corroded and brittle water mains to fail.

Frost Loads

There is another possible explanation for the greater breakage of pipes in cold areas: frost loads. Cold temperatures may frequently drive frost deeper into the ground, causing more rigid water pipes to break. During the winter of 1995, Scarborough, a suburb of Toronto, reported more than 160 breaks in one month alone: about one break every four hours for 31 consecutive days according to the Chlorine Chemistry Council (C3, 1998). Rajani and Zhan (1996), and Zhan and Rajani (1997) have presented methods in estimating frost loads on buried pipes in trenched and under roadways.

Traffic Loading and Pipe Depth below Surface

Francis (1994) has suggested that traffic loading causes water main breaks. However, Pascal and Revol (1994) have reported no obvious association exists between breaks, traffic loading and the position of pipes. Marshal (1999) has concluded that the response of fill to traffic loads was elastic and that no permanent increase in the external pressure of the pipe occurs.

Construction Method and Workmanship

The construction method and the workmanship of a pipe during its installation will definitely have an impact on how well a pipe may work throughout its service life. Inappropriate construction method and poor workmanship may result in an insufficient bedding or wrong material for fill, thus causing the pipe to bend and suffer more stress than is allowable, thereby resulting in the pipe's breaking. Pelletier et al. (2003) have suggested that in the City of Chicoutimi, pipes installed during the 1960s showed higher break rates compared to older pipes. Pelletier et al. attributed this to the probable poorer quality of material and installation techniques during the rapid growth period.

Cathodic Protection

Cathodic protection has been often used for water mains of cast iron and ductile iron. Researchers have showed that a well maintained cathodic protection program has changed the deterioration of water mains under certain circumstances (Gummow,1988; Doherty, 1990; Green et al., 1992).

Previous Pipe Breaks

All the factors listed in the above sections may cause a pipe to break. But what is exactly break? Clark et al. (1982) found that the definition of "break" is difficult to establish, a break may refer to a rupture of the line causing cessation of service. Their review showed that such ruptures are few compared to maintenance events or repairs. Their study analyzed the maintenance events or repairs where a leak was found. Maintenance crew took actions on joints and pipes. Repairs on valves or clamps were excluded from the study, for the valves and clamps were considered to be either internal or external fixtures and not a part of the pipe itself. Pelletier et al. (2003) defined a pipe break as a failure resulting in water leaking to the surface, thus necessitating an immediate intervention on the network. There are several major types of pipe breaks, circular or circumferential, longitudinal and holes. These types are mainly resulted from tensions and corrosion. Previous pipe break records have been used intensively for deterioration modeling analysis. Any pattern that may be identified in the break history can be used for forecasting future breakage of pipes assuming that this pattern will be carried over in future.

Water Quality

Infraguide (2002) has mentioned that aggressive water may cause water main corrosion (Table 2-1). However, little research has been done to quantify such impact resulting from various qualities of water sources. AWWARF (1996) has stated that pitting on water pipes is always associated with hard well waters with pH values in the range from 7.0 to 8.2. Lewis (1999) has analyzed corrosion causing the failure of copper pipe in water distribution due to water quality and chemistry used in treating potable water. C3 (1998) has mentioned that bio-films may build on internal pipe walls due to insufficient disinfection. Such bio-films are layers of bacteria that may attach most heavily to corroded surfaces on pipes and further contribute to pipe corrosion.

Al-Aghbar (2005) has discussed the following factors that have caused water main deterioration indirectly.

- Inadequate preventative maintenance and asset management: without proper preventative maintenance as part of a well established asset management program, the life expectancy of water mains may be significantly reduced.
- Inadequate funds and changed municipal priorities: new funds are more allocated to install new water distribution network rather than to repair and maintain old ones. (Shehab Eldeen, 2001)
- Lack of information and staff: lack of staff may have resulted in the insufficient information available for most Canadian municipalities.

To summarize the factors that affect the deterioration of water mains, Infraguide (2002) lists factors from the physical, environmental and operational point of view in Table 2-1.

2.4 Existing Statistical Deterioration Models

Kleiner and Rajani (2001a&b) have conducted comprehensive reviews of deterioration models of water mains. They have classified the models into two categories: physical/ mechanical models and statistical models. Physical/ mechanical models focus on predicting pipe failure by analyzing various loads to which a pipe is subject as well as the capacity of the pipe to resist these loads. Good physical / mechanical models are ideal for incorporating most inter-related factors that may cause a pipe to fail. However, the data that are necessary for these models may not be available or are very costly to acquire. Probably only large water mains may be able to justify the data collection needed for these models. Statistical models normally use the historical data on water main breakage to identify possible breakage patterns. These models assume such patterns continue in the future. The statistical models are further broadly classified into three categories: deterministic, probabilistic multi-variate and probabilistic single-variate group processing models (Kleiner and Rajani, 2001a). These statistical models are described in the following section.

2.4.1 Deterministic Models

Deterministic models use two or more parameters to model break patterns and are best applied to homogeneous pipe groups.

Shamir and Howard (1979) have proposed a deterministic time-exponential model in their economic analysis to determine the timing of pipe replacement. They have found the model in one study fitted the data.

$$N(t)=N(t_0)e^{A(t-t0)} \quad \text{.......... 2-1}$$

Where t= time in years,

t_0= base year for the analysis.

N(t)= number of breaks per 1000-ft length of pipe in year t,

A= regression parameter, growth rate coefficient (1/ year).

This model can be used to analyze pipe break data for an individual pipe, several pipes with similar characteristics, or a whole region of pipes. In their particular study conducted in 1976-77, the growth rate coefficient was found to have a range of 0.05 to 0.15, and the break rate of the base year, $N(t_0)$, ranged between 0.15 and 0.25 breaks /1000 ft/ year. Shamir and Howard (1979) have also assumed that the increase in breaks might be linear in the form as follows,

$$N(t)= N(t_0)A(t-t_0) \quad \text{.......... 2-2}$$

But no details on how this might fit the data was provided in the article.

After considerable testing, Walski and Pelliccia (1982) have found that the exponential form fitted the trends observed in Binghamton better than the linear

Table 2-1 Factors Affecting Deterioration of Water Mains

(Adapted from Infraguide, 2002)

	Factor	Explanation
Physical	Pipe material	Pipes made from different materials fail in different ways.
	Pipe wall thickness	Corrosion will penetrate thinner walled pipe more quickly.
	Pipe age	Effects of pipe degradation become more apparent over time.
	Pipe vintage	Pipes made at a particular time and place may be more vulnerable to failure.
	Pipe diameter	Small diameter pipes are more susceptible to beam failure.
	Type of joints	Some types of joints have experienced premature failure (e.g., leadite joints).
	Thrust restraint	Inadequate restraint can increase longitudinal stresses.
	Pipe lining and coating	Lined and coated pipes are less susceptible to corrosion.
	Dissimilar metals	Dissimilar metals are susceptible to galvanic corrosion.
	Pipe installation	Poor installation practices can damage pipes, making them vulnerable to failure.
	Pipe manufacture	Defects in pipe walls produced by manufacturing errors can make pipes vulnerable to failure. This problem is most common in older pit cast pipes.
Environmental	Pipe bedding	Improper bedding may result in premature pipe failure.
	Trench backfill	Some backfill materials are corrosive or frost susceptible.
	Soil type	Some soils are corrosive; some soils experience significant volume changes in response to moisture changes, resulting in changes to pipe loading. Presence of hydrocarbons and solvents in soil may result in some pipe deterioration.
	Groundwater	Some groundwater is aggressive toward certain pipe materials.
	Climate	Climate influences frost penetration and soil moisture. Permafrost must be considered in the north.
	Pipe location	Migration of road salt into soil can increase the rate of corrosion.
	Disturbances	Underground disturbances in the immediate vicinity of an existing pipe can lead to actual damage or changes in the support and loading structure on the pipe.
	Stray electrical currents	Stray currents cause electrolytic corrosion.
	Seismic activity	Seismic activity can increase stresses on pipe and cause pressure surges.
Operational	Internal water pressure, transient pressure	Changes to internal water pressure will change stresses acting on the pipe.
	Leakage	Leakage erodes pipe bedding and increases soil moisture in the pipe zone.
	Water quality	Some water is aggressive, promoting corrosion
	Flow velocity	Rate of internal corrosion is greater in unlined dead-ended mains.
	Backflow potential	Cross connections with systems that do not contain potable water can contaminate water distribution system.
	O&M practices	Poor practices can compromise structural integrity and water quality.

form of Shamir and Howard (1979). Instead of using an arbitrary base year t_0, Walski and Pelliccia selected year in which the pipe was installed as t_0, so that $(t-t_0)$ became pipe age (t-k), the exponential form was rewritten as,

$$N(t)=a\,e^{b(t-k)} \qquad \text{2-3}$$

Where t= time in years,

N(t)= break rate at age t- breaks/year/mile,

k= year of pipe installation,

a= regression parameter (breaks/ year/mile),

b= regression parameter (1/ year).

It was expected that there were separate sets of a,b for each size, for the previous break history, and for the type of pipe. However, due to the unavailability of data, only two sets were developed for pit and sand spun cast iron pipes. Walski and Pelliccia further developed correction factors that accounted for the higher break rates of pipes with previous breaks and larger size pit cast iron pipes, and the model was then rewritten as the following:

$$N(t)=c_1 c_2\, a e^{b(t-k)} \qquad \text{2-4}$$

Where c_1 = Break frequency[1]/ Overall break frequency[2]

c_2 = Break frequency[3]/ Overall break frequency[4]

[1] For (pit/ sand spun) cast iron with (no/one or more) previous breaks

[2] For (pit/sand spun) cast iron

[3] For pit cast iron pipe <500/>500 mm diameter

[4] For pit cast iron pipe

k= year of pipe installation.

Regression parameters and corrected factors in their specific study are given in Table 2-2.

Clark et al. (1982) have analyzed the number of maintenance events or repairs (but not actual ruptures) in their case study. Two underlying mechanisms were revealed in their examination of the data,

1) A lag period occurred between the time when the pipe was laid and the first maintenance event,
2) After the first event, the number of events seemed to increase exponentially.

Two equations were then developed as follows:

First Event Equation

$$NY=4.13+0.338D-0.22P-0.265I-0.0983RES-0.0003LH+13.28T \quad \text{.......... 2-5}$$

Accumulated Event Equation

$$REP=(0.1721)(e^{0.7197})^{T}(e^{0.0044})^{PRD}(e^{0.865})^{A}(e^{0.0121})^{DEV}(SL)^{0.014}(SH)^{0.069} \quad \text{......... 2-6}$$

Where NY=number of years from installation to first repair,

D= diameter of pipes, in inches,

P= absolute pressure within a pipe, psi,

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,

T= pipe type (1= metallic; 0= reinforced concrete),

REP= number of repairs,

PRD= pressure differential, psi,

A= age of pipe from first break,

DEV= percent of land over pipe in low and moderately corrosive soil,

SL= surface area of pipe in low corrosive soil,

SH= surface area of pipe in high corrosive soil.

The two equations need to be applied to each pipe individually to estimate the number of pipe breaks over time. In their particular study, R-squares were 0.23 and 0.47 for NY and REP respectively. Typical values for these two equations are listed in Table 2-3.

McMullen (1982) has made a regression analysis on the water distribution system of Des Moines, Iowa, US, and has proposed a model that predicts time to the first break of a pipe. It was observed that 94% of pipe failures occurred in soils of saturated resistivity of less than 2000 ohm cm, and one of best fit models is listed below:

$$Age = 65.78 - 0.028\,SR - 6.33\,pH - 0.049\,rd \qquad 2\text{-}7$$

Where Age= age of pipe at first break (years),

SR= saturated soil resistivity (ohm cm),

pH= soil pH,

rd= redox potential (millivolts).

Table 2-2 Regression Parameters and Correction Factors

(Adapted from Walski and Pelliccia, 1982)

Parameters	Pit Cast Iron	Sand spun Cast Iron
a	0.02577	0.0627
b	0.0207	0.0137
c_1-no previous breaks	0.654	0.682
c_1-One or more previous breaks	7.364	9.36
c_2(≥500 mm)	4.72	--
c_2(<500 mm)	0.887	--

The coefficient of determination (r^2) for this model was 0.375 and it should be noted that among the above factors, soil resistivity affects the age at first failure most, and an increase of 1000 ohm cm will reduce the age of first failure by 28 years.

Jacobs and Karney (1994) have examined the break data of Winnipeg, Canada, and have estimated the probability of occurrence of a day with no pipe breaks and the probability of the occurrence of an independent pipe break. Independent breaks are defined as those breaks which occurred more than 90 days after and/ or more than 20 meters from a previous break. Based on this definition, Goutler and Kazemi (1988), and Jacobs (1993) found that in Winnipeg, up to 40% of the breaks were non-independent ones. In Jacobs and Karney's (1994) analysis of 390 km of 150 mm cast iron water mains with about 3,550 breaks in Winnipeg, a linear regression form was developed for the water mains of three age groups

Table 2-3 Typical Values (Adapted from Clark et al. 1982)

Variable	Value
D	20.97 in (56.26 cm)
P	96.72 psi
I	3.35%
RES	34.43%
LH	2598 ft (791.97m)
T	1 metallic
PRD	33.47 psi
A	10.3 year
DEV	56.28%
SL	55.85 ft2
SH	76.54 ft2

(0-18, 19-30, and >30 years). At the beginning, the regression was applied to all breaks and the r^2 was from 0.704 to 0.937, and then it was applied to only independent breaks and the r^2 was improved to from 0.957 to 0.969. This correlation indicated that the independent breaks were uniformly distributed along the pipes. Their linear model is in a form as follows:

$$P' = a_0 + a_1\,Length + a_2\,Age \qquad \text{2-8}$$

Where P'= reciprocal of the probability of a day with no breaks,

a_0, a_1, a_2=regression coefficients.

Kleiner and Rajani (2001a) have criticized these deterministic models.

1) The exponential model of Shamir and Howard (1979) assumed a uniform distribution of breaks along all the water mains in a group, an assumption that was questioned by others, for example, Goulter and Kazemi (1988), Goulter, Davidson, and Jacobs (1993). However, this model is easy to implement when careful partition of data is warranted.

2) Similarly, the exponential model of Walski and Pelliccia (1982) also adopted the same assumption as that above. They have considered the difference of pit versus sand spun cast iron pipes, pipes of one break versus more breaks, and pipe sizes, which may have helped the prediction of break rates.
3) Clark et al (1982) were the first to account for several factors that were influential to pipe breaks. They considered two stages of pipe deterioration. The low r^2 of their linear model could indicate that the factors may act jointly rather than independently on the deterioration of a pipe, or that other factors were still be to considered and added. The moderate r^2 for the exponential model would suggest that more study is needed to justify this model.
4) McMullen's (1982) linear model was of an r^2 not high enough to be satisfactory. The model suggested that the factors affecting time to first failure were acting additively and independently. Questions may be raised on how the soil resistivity can be constant over a certain period of time.
5) Jacobs and Karney (1994) have provided useful information on independent breaks that were distributed uniformly along the pipes, but whether this was unique in Winnipeg or general elsewhere was still to be studied.

Hatfield (1987) used a power equation to predict the failures of metallic pipes. The model is as follows:

$$N(t)= at^{b} \qquad \text{2-9}$$

Where N(t) is number of repairs up to age t and a, b are regressions parameters. According to the author, this model provided satisfactory results for larger water mains. However, the author concluded in their report that prediction for specific mains can not be generated from water main data in large quantities.

2.4.2 Probabilistic Models

Probalistic multi-variate models can consider many covariates especially on individual water mains, but they require significant technical expertise and need sufficient data for analysis. Probabilistic single-variate group processing models use probabilistic analysis on grouped data to determine pipe life expectancy, and the probability of breakage.

2.4.2.1 Probabilistic Multi-Variate Models

Cox (1972) proposed a proportional hazards model which is a general failure prediction models with the following formula,

$$H(t,Z) = h_0(t)e^{b^T Z} \quad \text{...2-10}$$

Where t is the time to next break, h(t,Z) is the hazard function that defines the probability of failure at time t+Δt with survival time t. The arbitrary baseline hazardous function is $h_0(t)$, and Z is the vector of covariates acting multiplicatively on the hazard function, b is the vector of coefficients that can be estimated from regression.

Marks (1985) was the first to use proportional hazards model to predict water main breaks by calculating probability of time durations between consecutive breaks. Multi regression was used to determine Z that could affect pipe breakage rates, and one of the baseline hazards function was found as below.

$$H_0(t)= 2\times10^{-4}-10^{-5}t+2\times10^{-7}t^2 \quad \text{2-11}$$

Andreou et al. (1987a &b), and Marks et al. (1987) have further developed the proportional hazards model to include a two stage failure process. The first stage is the same as above, but in the second stage, the hazard function is expressed by

$$h = \lambda = e^{b^T z} \quad \text{2-12}$$

Andreou et al. (1987b) have reported r^2=0.34 and when pipes with 6 breaks or more are considered, r^2=0.46 for the second stage prediction. Eisenbeis (1994), Bremond (1997), and Lei (1997) have applied the proportional hazards models to water mains in Europe.

Lei (1997) has used an accelerated lifetime model to analyze water distribution systems in Norway and France, and it is of a form as follows:

$$ln(T) = \mu + x^T\beta + \sigma Z \Rightarrow f(\mu, \sigma Z)e^{x^T\beta} \quad \text{2-13}$$

Where T= time to (next) failure

x= vector of explanatory variables

Z= random variable distributed as Weibull

σ= parameter to be estimated by maximum likelihood

β= vector to be estimated by maximum likelihood

It was reported to have similar results to those of the proportional hazards model. However, no details on the model validation were provided.

2.2.2.2 Probabilistic Single-Variate Models

Hertz (1996) proposed a lifetime probabilistic (survival) model and applied it to pipes of the same material under similar environmental / operational conditions. The probability density f(t), hazards and survival functions h(t) and S(t) are defined by the following:

$$f(t) = \frac{(a+1)be^{b(t-c)}}{[a+e^{b(t-c)}]^2} \quad \text{..........} 2\text{-}14$$

$$S(t) = \frac{a+1}{a+e^{b(t-c)}} \quad \text{..........} 2\text{-}15$$

$$h(t) = \frac{be^{b(t-c)}}{a+e^{b(t-c)}} \quad \text{..........} 2\text{-}16$$

Where t= useful lifetime of pipe

a= aging factor ($year^{-1}$)

b= failure factor ($year^{-1}$)

c= resistance time(years), pipe will not be replaced before c.

Gustafson and Clancy (1999) used semi-Markov process to model the breakage history of water mains. The inter-break time t_i is considered as the holding time between state i-1 and state i. The semi-Markov process indicates that the inter-break time (or the time to the next break) is independent of the times between previous breaks, but is dependant only on the break order i. In their study, the time from the installation until the first break t_1 was modeled as a three parameter gamma distribution, and the rest of the inter-break times were modeled as exponential distributions. The breaks were found to decrease as i increased, meaning the higher the number of previous breaks on a pipe, the shorter the time that could be expected for its next break to come. In their study, the data sets of Saskatoon, Saskatchewan were applied. In this case, groups of pipes based on the wall thickness of the pipes were analyzed. It was found that the mean times until the first break from installation for thick, medium and thin wall pipes were 96, 44 and 34 years respectively. The expected times to the second or higher order breaks became smaller for all groups, which became almost constant: 2.1, 1.9 and 1.4 years for pipes from the 9^{th} to the 10^{th} break.

Kleiner and Rajani (2001a) have also criticized these probabilistic models.

1) The proportional hazards model is versatile to use and has a robust theoretical basis and the covariates have a multiplicative effect on the hazard function. This model is able to compare various pipe groups in water main network, but careful analysis is required to ensure that pipes of same or similar characteristics and environmental / operational conditions are formed. The second stage assumes a constant hazard function, meaning that, after their third breaks, pipes no longer age, this assumption conflicting with the corrosion process whereby pipe aging continues since corrosion always exists.
2) The accelerated lifetime model is similar to the proportional model except that the covariates act on the time to failure, so the failure hazard is affected in the proportional hazards model. It needs the same attention for data examination.

3) The lifetime probabilistic survival model can be a useful tool for forecasting the future financial needs of a water main network. It is applicable to large groups of water mains and is not suitable for individual pipes. It assumes that pipes are always replaced when they reach the end of their useful lives. There can be other reasons such as political, environmental reasons that initiate pipe replacement needs.
4) Gustafson and Clancy's (1999) model was able to predict inter-break times based on historic data, but they found their model inadequate for predicting future breaks.

2.5 Artificial Neural Network Model

Researchers have also used Artificial Neural Network(ANN) for deterioration modeling of water mains. Sacluti, Stanley and Zhang (1998) have applied ANN to the distribution system of a sub-division in Edmonton in order to identify areas that would have a higher cumulative probability of cast iron pipe failures. The model was trained with data that included temperature (water and ambient), rainfall, operating pressure and historical data on pipe breaks. According to a sensitivity analysis, rainfall and operating pressure did not contribute to the predictive power of the model, and then were excluded. The model demonstrated a strong forecasting ability for the cumulative breaks. However, the model has limitations since it was applied to a relative small pipe network without considering other factors such as soil, which could have severe impact on cast iron pipe deterioration. Zhang (2004) has further stated that while ANN can be a good tool in predicting the trend of water mains deterioration, it may be difficult to use ANN to pinpoint pipe breaks.

2.6 Condition Rating of Water Mains

As the majority of the municipalities are in short of capital funds in planning the repair, rehabilitation, and replacement of their deteriorated water mains, condition rating practices are very important in helping them to categorize their water main assets and allocate their limited budgets. Unfortunately, there is no standard condition rating practice so far. In practice, many municipalities have developed or are using customized weighting systems for rating their water mains. However, some municipalities may not even have such a system in place to help them do the decision making, and they rely mainly on the on-the-spot assessment of a pipe break to decide a follow-up solution. The rule of thumb as given by Morris (1975) was that a pipe needed to be replaced when there were three or more pipe breaks per 300 meters of the pipe. However, the manual did not give details how this was decided, and it did not mention the time interval between these three or more breaks. Walski and Pellicia (1982) have questioned this rule that, wondering, for example, whether, in a pipe of less than 99.9 meters, if one break has occurred, does the pipe need to be replaced according to this rule.

The existing practices from the Office of Water Services (OFWAT) in the U.K., and those of three municipalities in Canada are introduced here.

2.6.1 Condition Grading Practice of OFWAT UK

OFWAT (2002) has used a condition grading system since 1998. The criteria are a mix of life expectancy and performance (breaks per km per year). This grading is summarized in Table 2-4. Five grades are given with both qualitative and quantitative definitions.

This grading system focuses on burst frequency and the remaining useful life. Parson (2005) of OFWAT has commented that the burst frequency is an objective performance measure and is not well defined. Companies interpreted these criteria very differently to report their Condition Grade 4 and 5 mains with a range of 5% to 80% for one year. Those companies that put more weight on the performance side than the physical one (e.g. pipe wall thickness) reported their water mains to be in a much better overall condition. At the same time, the calculation of the number of bursts as indicated by the mains' condition grade profile reported by companies in their water mains inventory resulted in many times the number of bursts that actually occurred.

OFWAT (2002) has attempted to develop spatial indicators for the regulatory reporting of water mains. It suggested using GIS to divide the network into cells as shown in Figure 2-2. It further suggested the following cell sizing guidelines as shown in Table 2-5. It suggested that hot spot areas are, for example, cells with more than fifteen breaks in a three-year period. It provided guidance on how to analyse these cells thereafter. However, this proposal has probably not fully implemented yet, and there is no update available. According to Parsons (2005), OFWAT is currently reviewing its existing condition grading practices and is targeting to develop new ones to measure the serviceability of the water main network.

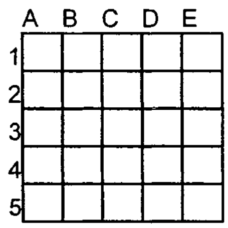

Figure 2-2 Cells to Divide Water Main Network for Spatial Analysis

(Adapted from OFWAT, 2002)

Table 2-4 Asset Condition Grades - Water Mains(Adapted from OFWAT, 2002)

Condition Grade	General Meaning
1	No failures, with steel, ductile iron or non-ferrous mains or communication pipes designed to current standards.
2	As 1, but not designed to current standards in relation to pressure ratings, manufacturer's specification of corrosion protection. Deterioration causing minimal influence on levels of service and less than 1 burst/km/annum.
3	Deterioration beginning to be reflected in deterioration levels of service and/ or increasing operating costs. Less than 3 bursts/km/annum. Assets replacement/ renovation required within 10 years.
4	Assets nearing end useful life, further deterioration likely, affecting levels of service with significant internal or external corrosion. Bursts from 3 to 5/ km/annum. Asset replacement/renovation required within medium term.
5	Assets substantially derelict with no residual life expectancy requiring urgent replacement/ renovation. Bursts greater than 5/km/annum.

Table 2-5 Cell Sizing Guidelines (Adapted from OFWAT, 2002)

Area	Equivalent Cell Size
City	0.5 km
Town/Sub-urban	1 km
Rural	2 km

Parsons (2005) has questioned the definition of a pipe length in calculating the number of bursts per km per year. In one of his studies, Parsons has used number of breaks divided by the distance between two breaks to grade a pipe. The key point is that two failures may help identify structural condition more easily than one failure for a specific pipe. The water mains were graded 1 (excellent) to 5 (worst) according to burst history over 4 years. Furthermore, Parsons has raised the questions on how leakage should be considered as a measure of performance, and on how performance and condition measures should be combined in defining new criteria for water main grading.

Table 2-6 Water Main Grading Based on Distance Between Failures (Adapted from Parsons, 1999 a &b)

Grade of main	Distance (km) between failures in four year record
1	More than 1
2	Between 0.5 and 1
3	Between 0.25 and 0.5
4	Between 0.125 and 0.25
5	Up to 0.125 (i.e. 8 or more bursts/km in four years)

2.6.2 Condition Rating Practice of Moncton

Isenor and Lalonde (2003) have used their Asset Management System (AMS) to assess the condition of individual pipe segments and to estimate the remaining service life of water mains in the City of Moncton, Canada. A full assessment using their systematic approach needs to incorporate indices such as physical (derived from pipe repairs, material, thickness and environment), functional (derived from capacity and water quality), associated infrastructures (fire hydrants, valves and private junctions), and socioeconomics (derived from claims, population, time, and traffic).

For the City of Moncton, Isenor and Lalonde (2003) have focused on only the development of the physical integrity index based on sub-indices for the break history, the pipe wall thickness, the pipe material and age. The sub-index of pipe material was developed based from pipe sampling, soil analysis, and original data according to material and installation. The sub- index of pipe thickness was developed from pipe sampling program. In Table 2-7, the sub index of condition based on pipe break history is given, and four categories are defined according to the level of services in terms of the number of breaks per 100 km per year. A pipe is assigned to the worst category if it has more than 50 breaks per 100 km per year (0.5 breaks per km per year). This sub-index will then be tied into the other two indices on pipe wall thickness and pipe material/age to obtain a final rating of a pipe.

2.6.3 Condition Rating Practice of Hamilton

The City of Hamilton, according to Bainbridge (2004), has been working to integrate roads, sewers, and water mains for municipal infrastructure management. As for water mains, it has been using weighted rating method in considering pipe properties (pipe material, diameter, age, and depth) and structural aspects (soil, hydraulic flow, annual break rates, and pressure differential) in order to get an overall condition index for each water main. This

Table 2-7 Condition Index on Pipe Breaks History

(Adapted from Isenor and Lalonde, 2003)

Condition Index Range	Condition Assessment	Improvement	Level of Services (breaks/100km/year)
1.0 to 0.75	A- Excellent	No action required	<5
0.75 to 0.50	B- Acceptable	Possible action in the long term	Between 5 and 15
0.50 to 0.25	C- Poor	An action is required in the short term	Between 15 and 50
0.25 to 0	D- Critical	An immediate action is required	>50

index will then be incorporated with other indices obtained from roads and sewers for an overall condition rating. It should be noted that as far as annual break rates are concerned, the City of Hamilton has a range from 0 to 25 plus breaks/km/year, indicating that, as far as break rates of individual pipes are concerned, the values vary significantly.

Table 2-8 gives the formulas to calculate the overall condition index from the physical and structural indices. Weightings are allocated to each factor in calculating overall physical and structural indices. Table 2-9 lists factors that contribute to the physical index of a water main. The factors include water main size, age, material and depth. Table 2-10 presents factors that affect the structural index of a water main. The hydraulic flow, differential pressure, previous break rates, and soil type are considered. All individual factors have scores between 0-1. The number 0 refers to the worst and 1 the best. Similar condition rating criteria have been developed for sewers and roads, and all three indices are further incorporated together for an overall condition rating of water mains, sewers and roads.

Table 2-8 Overall Water Main Condition Index

(Adapted from Bainbridge, 2004)

OWSI= [(Water Main breaks×0.5)+(Drop in Pressure×0.25)+(Soil Type×0.15)+(Hydraulic Flow×0.1)] ×100
OWPI= (Water Main Size+Water Main Age+ Water Main Material + Water Main Depth)/4×100
OWCI= OWSI× 0.7+OWPI× 0.3
OWSI (Overall Water Structural Index)
OWPI (Overall Water Properties Index)
OWCI (Overall Water Condition Index)

2.6.4 Condition Rating Practice of Edmonton

According to Cameron (2005), EPCOR Water Services Inc. owns and operates 3,400 km of water mains within the City of Edmonton, Canada. EPCOR experienced a tenfold increase of water main breaks while the length of water distribution system only doubled between 1952 and 1965. It was noted that cast iron pipes caused the majority of the breaks. EPCOR decided to discontinue the use of cast iron pipe for water distribution. It adopted 5 water main breaks per km-year as a renewal criterion in order to replace cast iron pipes in 1985 after experiencing 1,600 water main failures in one year. This methodology helped identify about 10 km of pipes per year for replacement. The replacement program was carried out for nearly 20 years. Between 2004 and 2008, as more focus is given to municipal infrastructures, additional funding has allowed EPCOR to replace approximate 20 km of water mains annually. However, the old renewal criterion was not able to identify enough pipes for replacement. In 2004, a new prioritization process was developed. The new criteria expanded from the singe break rate criterion to include the following characteristics:

- Hydraulics
- Water quality
- Demographics
- Economy of scale
- Water main condition and maintenance history

A new strategy was also added that looked into the condition of the water network at an area level. The rating of each area was included in the water main prioritization rating. EPCOR considered the inclusion of functional failures (hydraulic, water quality and reliability) in the decision making process as a Proactive Renewal Approach, compared to previous Reactive Renewal Approach which focused only on structural pipe failures.

Table 2-9 Factors for Calculating Water Main Overall Properties Index (Adapted from Bainbridge, 2004)

Water main Size		Water main Age		Water main Material		Water main Depth	
Network Pipe Size (mm)	Score	Age (years)	Score	Material Used	Scor e	Depth (m)	Score
300,100	0	>100	0	Cast Iron/ Lead Pipe/Galvanized/Alloy	0	<=1.0	0
250	0.2	76-100	0.2	Rehabilitated Cement Lined Cast Iron/ Rehabilitated Epoxy Lined Cast Iron/ Steel Pipe	0.4	1.1-1.2	0.2
200	0.4	51-75	0.4	Ductile Iron	0.7	1.4-1.5	0.4
150	0.6	36-50	0.6	Polyethylene Encased Ductile Iron	0.8	1.9-2.0	0.7
<=50	1	16-35	0.8	Hyprotec/Concrete /Hyprescon<500/Lafarg e C301	0.9	1.7-1.8	0.8
		0-15	1	Polyvinyle Chloride/Soft Copper	1	1.6	1

Table 2-11 shows a benchmarking on factors considered by Edmonton against the other six cities in Canada and the US. Three categories of factors are compared: the main characteristics of water mains, system characteristics and area characteristics (water main environment).

Tables 2-12 and 2-13 are used to rank different areas on GIS in which maintenance teams to group their works. These individual areas will be given a rating according to the water main area criteria and the threshold selection logic. The weightings of each component are given in Table 2-12. According to Cameron (2005), the actual ratings for these areas are less than 75%. The higher the rating is, the better the condition the area has.

Tables 2-14 and 2-15 work together to define the condition index of a cast iron pipe candidate for prioritizing purposes. The results will be a list of prioritized pipes developed from a combination of the thresholds and weightings. It need to be noted that for the EPCOR's prioritization rating system, a pipe candidate can be a pipe with sections of different materials and ages, while the City of Hamilton and the City of Moncton have focused on pipes that have same diameter, material, and age. This is a very different approach compared to others.

2.6.5 Condition Grading Practice of New Zealand

New Zealand Water and Wastewater Association (NZWWA, 1999) has established guidelines on infrastructure asset grading for water mains and other assets related to water and waste water. Note this grading scale in Table 2-16 has similar five grades to that of OFWAT (2002), refer to Section 2.6.1, Table 2-4 Asset Condition Grades - Water Mains. However, NZWWA's scale has not incorporated any number of breaks per kilometer per year to its Grade 2 to 4 conditions. The engineers determine the condition grades of water mains by reviewing water main surveys, failure reports and sampling results, etc. The surveys are conducted by the operators according to the Water Utility Field Inspection Cards. The cards need to collect information on water mains such as location, surface use, ground type, surface material, pipe or fitting details (material, joint, bedding and surround, external/ internal protection, diameter, depth), failure and corrosion.

NZWWA (1999) has also proposed a "1 to 5" Performance Grading Scale for water mains, which are related to the capability of assets to meet defined service criteria. This performance grading is mainly associated with the water quality that results from loose pipewall deposits or deterioration of linings in the water pipes. The performance and condition grading for water mains are core in their overall asset management approach.

Table 2-10 Factors for Calculating Water Main Overall Structural Index (Adapted from Bainbridge, 2004)

Hydraulic Flows		Difference in Static Hydraulic Pressure and Residual Hydraulic Pressure		Water Main Breaks		Soil Type		
Hydraulic Flow (gpm)	Score	Difference (psi)	Score	Number of Breaks/km/year	Score	Soil Type	Soil Corrositivity Factor	Score
<450	0	>30	0	>25	0	Mixed Landfill Material	14	0
450-649	0.2	26-30	0.2	20-25	0.2	Clay	13	0.1
650-849	0.4	21-25	0.4	15-13.99	0.4	Silty Clay	12	0.2
850-1049	0.6	16-20	0.6	10-14.99	0.6	Shale	11	0.3
1050-1250	0.8	10-15	0.8	0-9.99	0.8	Clayey Silt	10	0.4
>1250	1	<10	1	0	1	Silt	9	0.5
						Silty Sand	8	0.6
						Sandy Silt	7	0.7
						Recent Deposit Gravel	6	0.7
						Sand	5	0.8
						Alluvial Fan Gravel	4	0.9
						Lake Iroquois Beach Gravel	3	0.9
						Lake Iroquois Gravel	2	1
						Dolomite Limestone Bedrock	1	1
						Soil resistivity indicates that 1 is least corrosive and 14 is most corrosive		

Table 2-11 Criteria Used by Various Utilities for Water Main Replacement Evaluation (Adapted from Cameron, 2004)

Criteria	East Bay MUD	Philadelphia	Denver	Louisville	Scarborough	St. Catherines	Edmonton
Main Characteristics							
Age		X	X	X	X		X
Size		X	X	X	X	X	X
Depth			X		X		
Corrosion		X	X	X			X
Dead End Main		X		X		X	
Type of Material or Joint		X	X	X			X
Break/Leak History	X	X	X	X	X	X	X
Type of Lining					X		
System Characteristics							
Water Quality	X	X		X	X		X
Water Pressure	X	X	X	X	X		X
Operational Flexibility	X	X				X	
Reduced Pumping Costs	X						
Secondary Reinforcing Main		X					
Increased Carrying Capacity	X	X	X		X	X	
Area Characteristics							
Soil Data			X	X			
Electrolysis		X					
High Priority Zone	X			X		X	X
Development Zone	X	X	X	X	X		X
Cost Analysis							
Cost of Maintaining	X						X
Cost of Replacing	X						X
Rate of Return on Investment	X						X

Table 2-12 Water Mains Area Criteria and Threshold Selection Logic

(Adapted from Cameron, 2005)

Criteria	Threshold	Reasoning
% Cast Iron	20% intervals - even	The more cast iron, the more failures likely to occur.
% 100mm Cast Iron	2% intervals – the largest value was under 10%	100mm cast iron tends to be very old with poor hydraulics, but due to their thicker walls have fewer structural failures.
Breaks/km/5yr	0.0005 intervals – the largest value was not much more than 0.0025	Describes the failure rate.
Hydroscope – a pipe wall inspection process	Intervals chosen based on what seemed like moderate break points	The more holes found with the pipe wall inspection tool, the higher the chance of failure.
Low Flow (less than 60 L/s)	2.5% intervals – the largest percentage was around 10%	Any flows under 60 L/s are extremely poor.
Roughness	Similar to other Utilities	Roughness is a direct reflection of the hydraulics.
Minimum Available Flow	Break points based on fire fighting requirements	An indication of whether or not there are hydraulic issues in the area.
Average Available Flow	Break points based on fire fighting requirements	An indication of whether or not the area generally has poor hydraulics.
Frequency	Yearly	The flushing frequency is an indication of how poor the water quality is in an area.
Water Quality Complaint	20 complaint interval based on not having any more than 100.	An indirect indication of the water quality in an area.
Long Flush	Intervals chosen based on what seemed like moderate break points	An indirect indication of the water quality and the hydraulics in an area.

Table 2-13 Water Mains Area Cast Iron Weightings

(Adapted from Cameron, 2005)

Area Components	Weighting (100%)
Condition/Material/Maintenance History Components	45%
% CI	15%
% 100 mm CI	5%
Breaks/km/5 year	15%
Hydroscope	10%
Hydraulic Components	30%
Low Flow Nodes	5%
Roughness	5%
Minimum Available Flow	10%
Average Available Flow	10%
Water Quality Components	25%
Long Flushing Times	10%
Flushing Frequency	5%
Water Quality Complaints	10%

Table 2-14 Water Mains Candidate Criteria and Threshold Selection Logic

(Adapted from Cameron, 2005)

Criteria	Threshold	Reasoning
Total Breaks	Every 5 – based on the maximum noted being not much larger than 20.	Breaks that have occurred – even if not recent – reflect the condition of the main.
Land Use	Grouped based on fire flow requirements.	Provides information about fire flow requirements while also providing some information about possible impacts that could place additional stress on the main.
Road Type	Grouped based on the cost to repair the main break and the inconvenience due to traffic disruption.	Adds priority to roads that cause more traffic disruption while also providing information about possible impacts that could place additional stress on the main.
Number of Customers	Every 10 – based on the maximum noted being not much larger than 40.	Allows for importance to be given to customer service as well as loss of revenue.
Installation Year	Grouped based on those that would have high failures or very poor hydraulics.	Allows for importance to be given to those mains that seem to be problem years.
Length of CI in Candidate	50 m intervals based on most candidates being not much longer than 200 m	Allows for larger projects to get slightly higher priority.

Table 2-15 Water Mains Candidate Cast Iron Weightings

(Adapted from Cameron, 2005)

Candidate Components	Weighting (100%)
Condition/Break History Components	40%
RPV	25%
Total Breaks	10%
Hydroscope	5%
Demographic Components	25%
Land Use	10%
Road Type	5%
Number of Customers (Services)	10%
Hydraulic Components	15%
Fire Flow	10%
Installation Year	5%
Water Quality Components	15%
Extended Flushing + Water Quality Calls	10%
Area Components	5%
Condition/Material/Break History Components	2.25%
Hydraulic Components	1.50%
Water Quality Components	1.25%
Economies of Scale Components	5%
Length of CI in Candidate	5%

Table 2-16 Water Main Condition Grading (Adapted from NZWWA, 1999)

Condition Grade	General Meaning
1	**Very Good** Modern pipe material designed to current standards with no pipewall or joint failures and no evidence of internal or external degradation
2	**Good** As condition 1 but not designed to current standards in respect of pressure ratings, design specification, jointing or corrosion protection. Deterioration causing minimal influence on performance.
3	**Moderate** Water mains which are generally sound, although with a few pipewall or joint failures or evidence of some external or internal degradation. Some deterioration beginning to be reflected in performance.
4	**Poor** Water mains or sewage pumping mains with a significant level of pipewall or joint failures or evidence of significant external or internal degradation causing, or likely to cause a marked deterioration in performance in the medium term. Some assets replacement or rehabilitation needed within the medium term.
5	**Very Poor** Unsound water mains with extensive pipewall or joint failures, or significant external or internal degradation, which has failed or about to fail in the near future, causing unacceptable performance. No life expectancy, requiring urgent replacement or rehabilitation.

2.7 Multiple Regression Modeling

The application of probabilistic (proportional hazards, accelerated life, lifetime survival, and semi-Markov chain) models in general requires more data than are typically available from municipalities. For example, Kleiner and Rajani (2001a) have remarked that due to the lack of data in most municipalities, the proportional models have been limited in use. Marvin (1996) has stated a full break history of a pipe to predict the inter-break time by using an exponential model. However, a complete life cycle data of water main break history are rarely available. The deterministic statistical models in literature have considered one or more factors to forecast break rate, number of years until first break and accumulated number of breaks. Statistics on multiple regression modeling are briefed below.

Multiple Regression Equation

A general multiple regression form for p independent variables is given as follows:

$$Y=\beta_0+\beta_1X_1+\beta_2X_2+\cdots+\beta_pX_p+\epsilon \quad \text{......2-17}$$

Where, Y denotes a dependent variable (or response)

X_i denotes an independent variables (or predictors)

β_i denotes a regression coefficient that need to be estimated

ϵ denotes a random variable that has mean 0 at fixed x_i

The least-squares method is often used to estimate the regression coefficients β_i, which minimizes the sum of squares of the distances between the observed responses and those predicted by the fitted model. In other words, the better the fit model is, the smaller the deviations of observed from predicted values are. Thus, for the best fitted regression model obtained from this method, as shown in Equation 2-18, the sum of squares of deviations (SSE) of observed Y values from corresponding predicted values, as given by Equation 2-19, will be the smallest. The minimum sum of squares is generally called the residual sum of squares.

$$\hat{Y}=\hat{\beta}_0+\hat{\beta}_1X_1+\hat{\beta}_2X_2+\ldots+\hat{\beta}_pX_p \quad \text{......2-18}$$

$$\sum_{i=1}^{n}(Y_i-\hat{Y}_i)^2=\sum_{i=1}^{n}(Y_i-\hat{\beta}_0+\hat{\beta}_1X_{1i}+\hat{\beta}_2X_{2i}+\ldots+\hat{\beta}_pX_{pi})^2 \quad \text{....2-19}$$

Best Subsets Regression

In order to find the best predictive model, higher-order terms (e.g. X_i^2), interactions of first-order terms (e.g. $X_1 x X_2$) as well as some others can be considered as the independent variables (Kleinbaum and Kupper, 1978). Best subsets regression is a procedure that enables the user to find a group of likely models for further analysis, given specific independent variables. The general method is to select the smallest subset of variables that fulfills certain statistical criteria rather than a full set, because the subset model may actually estimate the regression coefficients and predict future responses with smaller variance than the full model using all predictors. The statistics R square, adjusted R square, Mallows Cp, and s (square root of the error mean square, MSE) are calculated by the best subsets procedure and can be used as comparison criteria. Typically, subsets that provide the largest R square value are considered. However, in the best subsets regression, R square always increases with the size of the subset. For example, the best five-predictor model always has a higher R square than the best four-predictor model. Therefore, R square is most useful when comparing models of the same size. When comparing models with the same number of predictors, choosing the model with the highest R square is equivalent to choosing the model with the smallest SSE(the sum of the squared deviations). One should use adjusted R square and Cp to compare models with different numbers of predictors. In this case, choosing the model with the highest adjusted R is equivalent to choosing the model with the smallest mean square error (MSE).The Cp statistic is given by the formula (Cp = (SSEp / MSEm) - (n-2p)). The SSEp is SSE for the best model with p parameters (including the intercept, if it is in the equation), and MSEm is the mean square error for the model with all m predictors. In general, one should look for models where Cp is small and close to p. If the model is adequate (that is, fits the data well), then the expected value of

Cp is approximately equal to p (the number of parameters in the model). A small value of Cp indicates that the model is relatively precise (has small variance) in estimating the true regression coefficients and predicting future responses. This precision will not improve much by adding more predictors. Models with considerable lack of fit have values of Cp larger than p (Minitab Software, 2002).

Multiple Regression and Testing of Significance

By following the above guidelines for best subsets selection, subsets that have relatively high adjusted R square values and that Mallows CP values close to number of variables, p, are chosen for continuing with multiple regression analysis in Minitab Software.

In the multiple regression, models with estimated regression coefficients as well as analysis of variance are generated. Two tests need to be conducted to determine statistical significance of a model: the F test and t test. The F test is used to determine whether a overall significant relationship exists between the dependent variable and the chosen set of independent variables. This test is also called overall significance test. If F test shows the relationship is significant. A t test will have to be conducted with each of the independent variables. These tests are called individual significance tests (Anderson et al. 2002). For a multiple regression model of Equation 2-17, the F test and the t test are explained below:

F Test for Overall Significance

$H_0: \beta_1 = \beta_2 = \cdots = \beta_p = 0$

H_a: One or more of the parameters is not equal to zero.

Test Statistic

F= MSR/MSE..**2-20**

Rejection Rule

Using test statistics: Reject H_0 if $F > F_\alpha$

Or: Using p value: Reject H_0 if p-value$<\alpha$

where F_α is based on an F distribution with p degrees of freedom in the numerator and n-p-1 degrees of freedom in the denominator

t Test for Individual Significance

For any parameter β_i

$H_0: \beta_i = 0$

$H_a: \beta_i \neq 0$

Test Statistic

$t = b_i/S_{bi}$..**2-21**

Rejection Rule

Using test statistic: Reject H_0 if $t < -t_{\alpha/2}$ or $t > t_{\alpha/2}$

Or: Using p value: Reject H_0 if p-value$<\alpha$

Where $t_{\alpha/2}$ is based on a t distribution n-p-1 degrees of freedom.

When the model passes both F test and t test, it is statistically significant, which mean that the dependent variable (response) and the independent variables (predictors) have a significant relationship. Statistical software, such as Minitab, produces both the F test and t test results simultaneously along with a regression equation.

Model Validation

Models of significance then go through a validation process. According to Zayed and Halpin (2005), two equations 2-22 and 2-23 can be used to validate a model. Equation 2-22 represents the average invalidity percent (AIP), which shows the prediction error, and Equation 2-23 refers to the average validity percent out of 100.

$$AIP = \left(\sum_{i=1}^{n} \left|(1-E_i/C_i)\right|\right)/n \quad \text{2-22}$$

$$AVP = 1-AIP \quad \text{2-23}$$

Where AIP=Average Invalidity Percent

E_i= Estimated/ Predicted Value

C_i= Actual Value

AVP= Average Validity Percent.

After all the above procedures are done, a sensitivity analysis is conducted to examine the individual independent variables to see how each of them may affect the dependant variable while the other independent variables remain constant.

2.8 GIS in Water Main Asset Management

As a computer system for capturing, storing, checking, integrating, manipulating, analyzing and displaying data related to positions on the Earth's surface, GIS has been one of most popular tools in today's municipal infrastructure management environment. The spatial features associated with GIS have allowed municipalities to manage their water main assets as well as other assets such as sewer, road, and bridge assets. The surveys on GIS usage in civil engineering have confirmed this popularity (McMahon, 1997; GITA, 2002, Vanier, 2004).

The application of GIS to municipal infrastructure including water mains varies. Vanier (2004) has surveyed four cities and four regional municipalities in Canada during the Municipal Infrastructure Investment Project (MIIP), showing that the majority reported that they are using GIS for data storage, mapping, data exchange, decision support, engineering analysis, and planning. The desired activities using GIS also include work management, client information, document management, and executive information. However, few municipalities foresaw opportunities for using GIS for maintenance management (monitoring and complaint records) or failure mode analysis. Municipalities use GIS to create links among geographical data, relational databases (pipe characteristics, break history), and modeling tools. The Cities of Laval and Quebec (Ste-Foy) have used GIS to manipulate water main data consisting of pipe characteristics and break history; the City of Saskatoon has reported using GIS to support economic analysis of sewer main rehabilitation projects (Clancy et al. 2002); the City of Hamilton used GIS in developing an integrated infrastructure management system for water mains, sewers and roads (Bainbridge, 2004).

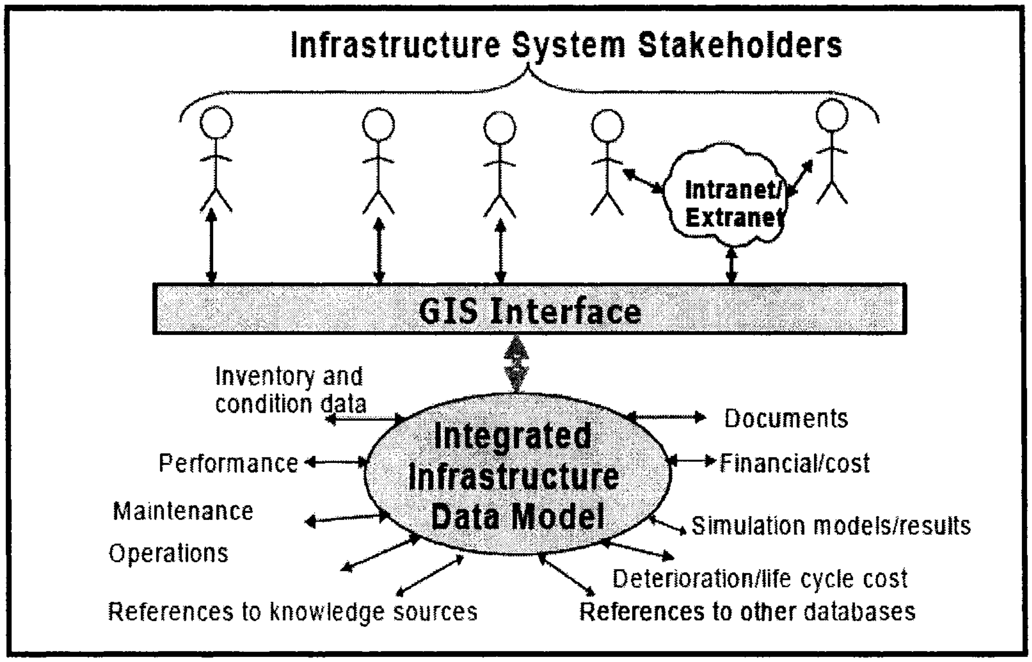

Figure 2-3 A Model-Based Approach to Municipal Asset Management

(Adapted from Halfawy et al. 2002)

Pipe assessment software applications developed in Europe, which can be used for water main analysis, such as AssetMap, Genini VA, KureCAD and Utilnets have integrated GIS user interface (Stone et al., 2002). The Seattle Public Utilities created a user friendly interface with GIS to rank pipelines and to prioritize the repair, replacement, or rehabilitation of pipelines (Lim and Pratti, 2001). Halfawy et al. (2005) have reviewed state-of-the-art, commercial, off-the-shelf municipal infrastructure asset management systems. All the asset management software systems (Synergen, CityWorks, MIMS,Hasen, RIVA, Infrastructure2000, and Harfan) either are GIS based or can interface with GIS.

Halfawy (2004) has researched the interoperability of GIS for municipal asset management applications and presented strategies for Canadian municipalities to take in order to further enhance the sharing and exchanging spatial data about infrastructure assets. As can be seen in the model-based approach for infrastructure management (See Figure 2-3) of Halfawy et al. (2002), GIS will become even more important in helping municipalities with the management of infrastructure assets.

Al-Aghbar (2005) and Al-Aghbar et al. (2005) have developed a decision support system to help select the proper rehabilitation method(s) using trenchless technology to solve the problems of service defects (poor water quality and hydraulic performance) as well as structural defects of water mains. If more than one rehabilitation methods are applicable to one case, the Multi-attribute Utility Theory and the Analytical Hierarchy Process are adopted to choose the best rehabilitation method. However, Al-Aghbar (2005) has assumed that the decisions to rehabilitate or replace a pipe have already been made by municipalities. No information is provided on the decision making process, which may include condition rating analysis of individual pipes. The present study intends to work on deterioration models and condition rating practices in order to help make such decisions.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 General

Research on water main deterioration and prioritization has gained more attentions in recent years. The present research is intended to analyze and understand the progress in these two areas from both practical and academic perspectives. It is planned to benefit from municipalities in Canada as well as water authorities/ organizations world wide.

3.2 Proposed Research Methodology

Figure 3-1 shows the developed methodology in order to conduct the present research work. Data collection and analysis come along with literature review on water main deterioration, condition rating (prioritizing), and statistical analysis (regression). The existing models from literature are applied to the collected data sets to check their applicability. New models are developed. Validation and sensitivity analysis are conducted for the developed models. A condition rating scale is proposed, and followed by conclusion for the present research.

3.2.1 Literature Review

Literature review focuses on factors that affect the deterioration of water mains, existing deterioration models, current condition rating practices, GIS applications in water main asset management, and statistics on regression modeling. The literature review has been conducted by reaching out municipal engineers,

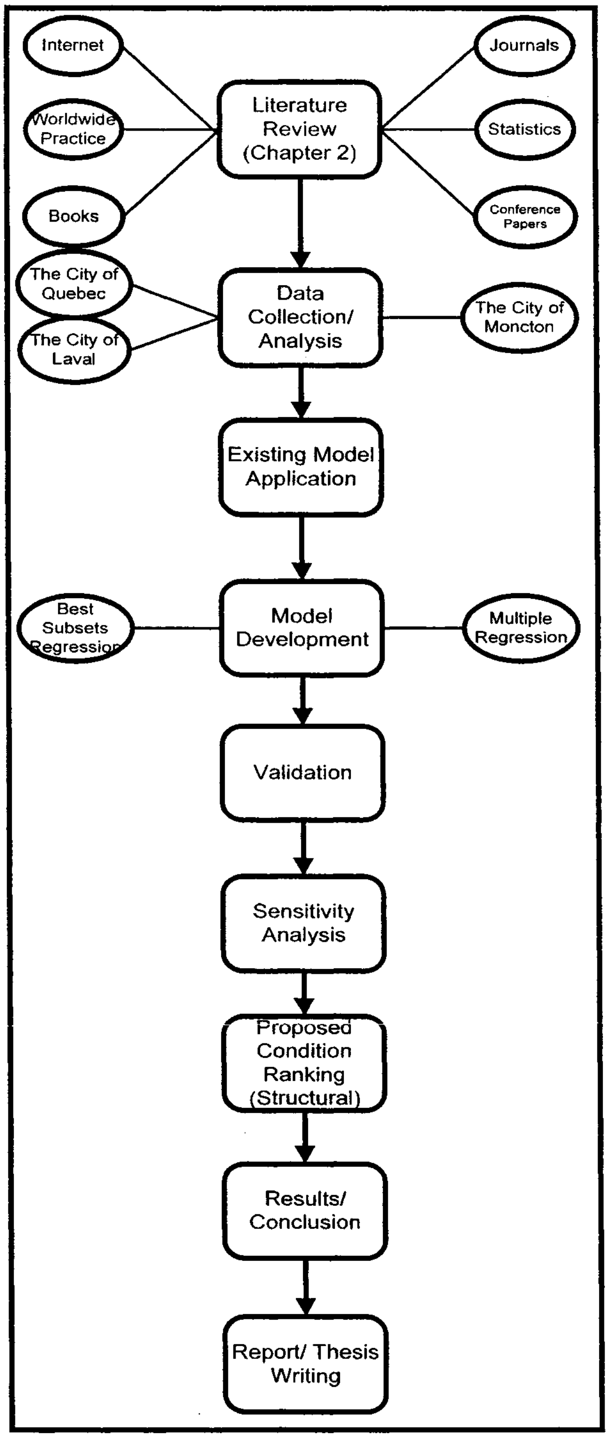

Figure 3-1 Research Methodology Diagram

researchers, and by reading journal, conference papers and related books.

3.2.2 Data Collection and Analysis

Data on water main break history and physical characteristics have been collected from three municipalities, namely, the City of Quebec (Ste-Foy), the City of Laval, and the City of Moncton through e-mail communications, interviews, meetings, and field trips. Data have been received in hardcopy format as well as in electronic (GIS, Microsoft Excel) formats. These three municipalities are considered because they have large, typical water distribution networks. Data analysis has been done to check out pipe lengths against material, diameter, and age as well as breaks against age, diameter, and pipe length, etc.. A detailed report on data collection and analysis are presented in Chapter 4.

3.2.3 Existing Model Application

It is intended to apply the existing deterioration models to the collected data sets to find out their applicability as well as limitations in order to improve their performance. The exponential models of Shamir and Howard (1979), and Walski and Pelliccia (1982) are two models that can be applied to the available data set of Quebec (Ste-Foy). However, these two models are applicable mainly on homogeneous pipe groups. The collected data in the present study are not sufficient to apply other models from the literature. The application of the above two exponential models to the Quebec data is not satisfactory.

3.2.4 Model Development

The present study takes another approach to focuses on individual water mains in terms of the annual break rate rather than on homogeneous group of water mains. The annual break rates have been commonly used by municipalities as a performance benchmark and as a controlling criterion in rating water main's conditions. It is expected to use the developed models on the annual break rates to establish a condition rating scale that can be used for prioritizing water mains for decision making. The present study plans to analyze the relationship between the annual break rates and pipe age, length, diameter, depth of installation, material type, traffic loading, soil condition, pressure, water quality, cathodic protection, previous repair/ rehabilitation methods, and previous replacement. In Quebec, only data on the annual break rate, pipe age, length, diameter, depth of installation, material type are available. These data are used to develop multiple regression models that are able to forecast the annual break rate of a water main from its pipe age, length, diameter, depth of installation, and material type.

The GIS file of water main data from the City of Laval does not have a pipe level association between breaks and individual pipes. The breaks in Laval are recorded on the properties that are adjacent to the water mains rather than on the water mains themselves. Thus, the annual break rates of the individual water mains can not be established in the present study.

The water main data from the City of Moncton have some inconsistencies. The break data in Microsoft Excel format have recorded individual breaks against the streets on which the breaks occurred, but not against the individual water mains. Only a selected group of water mains (172 Km out of the total network 517 Km) have the information on annual break rate, pipe length, age, diameter that can be used in the present study. Compared to the Quebec data, the Moncton data do not have information on the pipe depths.

Figure 3-2 shows the proposed model development for the present research work. It explains the procedures that are needed to develop valid deterioration models.

3.2.4.1 Best Subsets Regression

The relationship between annual break rates of individual water mains and the independent variables, such as pipe characteristics [age (A), size (S), length (L)] and others [depth (D)] is studied in the present research.

In order to find out the best fits, first order terms, higher order terms, and interactions of first order terms have been included as new independent variables. Furthermore, as the deterioration rate is always positive, the logarithms (logarithms to the base of 10) of annual break rates (number of breaks/km/year) are used as the dependent variable Y in the regression analysis against various forms of independent variables. This ensures the forecasted break rates to be always positive.

Best subsets regression is able to help select the best subsets of the independent variables that should be used for further multiple regression modeling. The details on how to select the best subsets have been discussed in Chapter 2.

3.2.4.2 Multiple Regression

Once a best subset is found in the Best Subsets Regression, a multiple regression model can be built with the Statistical Software (e.g. Minitab Software). Minitab is able to provide model equations, R^2, p statistics to determine testing of significance.

3.2.4.3 Testing of Significance

The p statistics given by the multiple regression in Minitab Software can help determine whether the model generated has an overall significance (F-test) and an individual significance (t-test). Only when both tests of significance are passed, this model can be considered as a statistically significant model.

3.2.4.4 Model Validation

Developed models are planned to be validated by using selected data that are not used in the model development. The validation is done according to Zayed and Halpin (2005), which has been described in the Chapter 2. Only the models with good results on the F test and t test will go through a validation process.

3.2.4.5 Sensitivity Analysis

If the model is valid, a sensitivity analysis will be conducted to examine how the independent variables (e.g. pipe age, length and diameter and depth) may affect the dependent variable (annual break rates, number of breaks/km/year). Models developed for different pipe material can be compared in the sensitivity analysis too.

3.2.5 Proposal of a New Condition Rating Scale

Developed deterioration models are intended to be used determine critical annual break rates for water mains so that a new condition rating scale can be proposed.

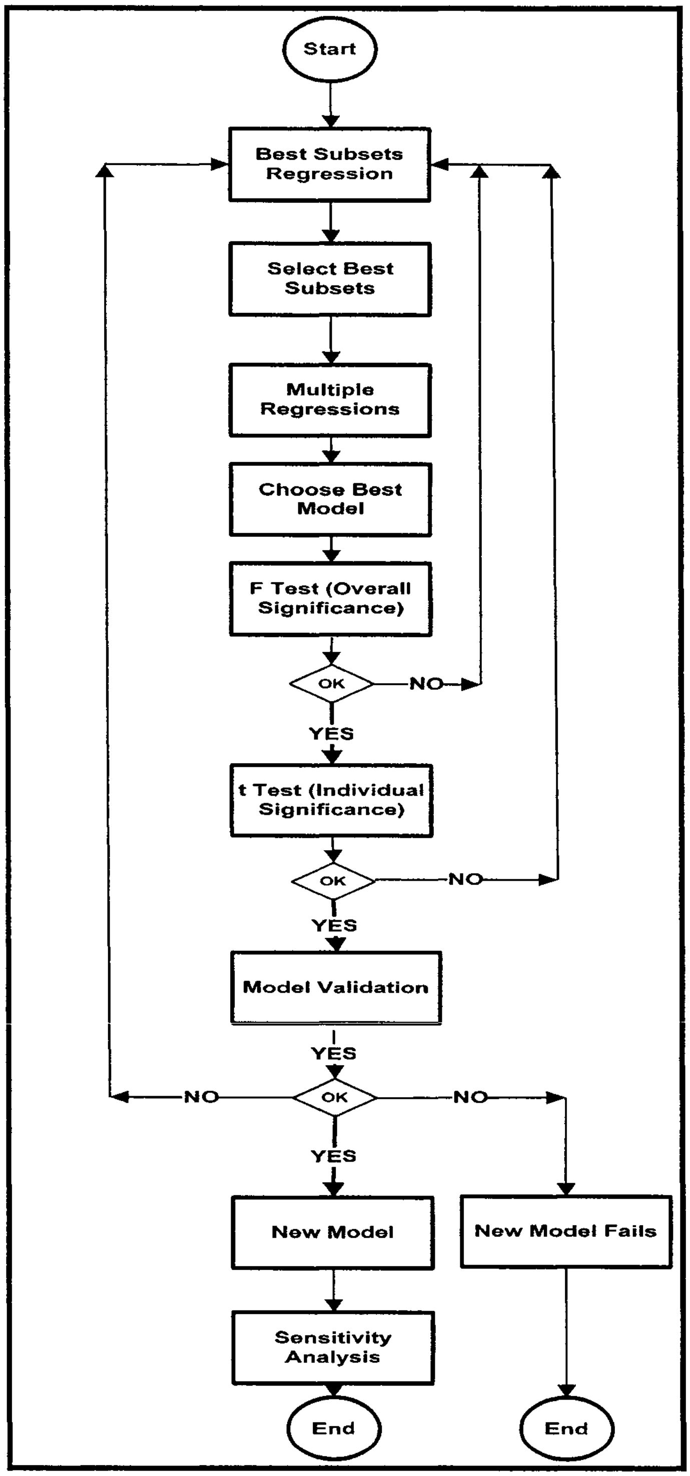

Figure 3-2 Proposed Modeling Methodology

CHAPTER 4

DATA COLLECTION AND ANALYSIS

4.1 General

Data collection has been key to this present research. Three Municipalities in Canada were contacted for obtaining water main data. The data have been collected in both electronic (GIS, Microsoft Excel, Acrobat PDF) formats and hard copies.

4.2 Data Collection and Preliminary Analysis

The data have been collected from three different municipalities, namely, Quebec (Ste-Foy), Moncton, and Laval in Canada through e mail communications, meetings, telephone calls, and field trips. The total lengths of the water distribution network are 1,603 Km, 517 Km, 432 Km for Laval, Moncton, and Quebec (Ste-Foy) respectively. Quebec (Ste-Foy) is referred to as Quebec hereafter. In the present research work, attempts have been made to collect water main data on the following:

- Operation and maintenance data of water mains
    a) Identification of water mains in the network and associated drawings
    b) Pipe material/ class
    c) Pipe size
    d) Date of installation
    e) Break history for water mains
        i. Date of breaks

ii. Number of breaks per km per year of water mains

iii. Classification of breaks

iv. Maintenance records for repairs or replacements

1. Date of repairs or replacements
2. How the breaks were detected
3. How the repairs or replacements were done
4. Costs of repairs or replacements

f) Internal pipe operating pressures

g) Surrounding soil conditions/ traffic conditions

h) Cathodic protection for metallic water mains

i. Date of installation

ii. Noticeable results

- Factors considered in decision making to either repair or replace a water main
- Data managed by Geographic Information System (GIS)

i) Location of water mains and their characteristics such as material/size/length etc.

j) Surrounding soil conditions such as types of soils

k) Break history and other maintenance records

Unfortunately, not all the data are available. The typical data collected in the present study can be referred to Table 4-2. As for the Laval data, pipe break records are not associated with individual pipes. A similar problem exists with the Moncton data (refer to Table 4-1), only pipes in the partial water main network of

172 Km in length have annual break rates, pipe lengths, diameters, ages, and material types, which are used for analysis and model development.

Table 4-1 shows a summary of water main material, length, and total number of breaks of the City of Moncton. It can be seen that there are some inconsistencies between the break data of the total water main network and those of the partial water main network. For example, in the break data for the whole network (517 Km), there are only 50 breaks of ductile iron pipes, but in the break data for the partial network (172 Km), there are 215 breaks listed. Attempts were made to clarify the inconsistencies with the engineers in Moncton. However, no results have been received. The break data for the whole network has a total 2,804 breaks that were recorded along with street names, and were not associated with individual pipes. Only the break data in the partial network, which is of 1,652 breaks, can be utilized and analyzed in the present study.

Table 4-2 shows a summary of the available data from Quebec and Moncton. For example, Quebec has pipe depth information, while Moncton has not. Moncton has partial soil and pavement information for the individual breaks, but not for the individual water mains in the partial network that is of 172 Km in length.

The descriptive statistical analysis is conducted for the Quebec and Moncton data. A detailed presentation is provided for the Quebec data in the present chapter.

4.3 Data Filtering and Organization

The following steps have been done for filtering and organizing the Quebec data:

- Data are retrieved from GIS databases.
- Breaks records are associated with individual pipes.
- Data are grouped by pipe material type.
- Inconsistent data are identified and removed. For example, data that fall into the following categories are removed from further analysis.
  a) Break dates are earlier than pipe installation dates.
  b) There are data that are missing from the information of the pipes or breaks, such as diameter, length, date of installation, material type, and date of break.
  c) Pipes of certain materials have very few break records and minimum lengths in the water main network, such as copper and steel pipes.
- The lengths of the pipes with the same ages are added and the breakdowns of the number of breaks by year are listed.
- Groups of pipes are established according to material, diameter and periods of installation.
- The numbers of breaks are also totaled for individual pipes.

Table 4-3 shows the number of breaks by material and the amount of data being filtered according to the above mentioned filtering categories. 11% of the total 1,785 breaks are filtered. 1,581 breaks are used for model building and further analysis.

Table 4-4 shows a breakdown of total number of breaks per year for pipes of the same age and diameter. For example, the 11,022 meters of 150 mm Grey Cast Iron pipes that were installed in 1954 have 95 breaks from 1987 to 2001,and 11 breaks in 1999.

Table 4-5 shows a breakdown of number of breaks per year for pipes of different diameters and decades of installation for the Grey Cast Iron, Ductile Iron Lined and Not Lined pipes. For example, the 130 km Grey Cast Iron pipes have 755 breaks in total. The 67 Km Ductile Iron (Not Lined), and the 70 Km Ductile Iron (Lined) pipes have 314, and 289 breaks respectively.

Table 4-6 shows details (total number of breaks, date of breaks, type of break, pipe material, year of installation and pipe diameter) of individual pipes in the GIS database. For example, the 99-m, 600 mm Grey Cast Iron pipe (Pipe I.D. 8159) installed in 1959 has 5 breaks in total from 1987 to 2001.

Table 4-7 shows pipe ages at which the Grey Cast Iron pipe groups had breaks. For example, for the 1,293-m, 150 mm Grey Cast Iron pipe group installed in 1951, between 1987 and 2001, there are 1, 2, 2, 1, 2, 1,1 breaks at the ages 37, 38, 40,41,42,46 respectively. It should be noted that some pipe groups (e.g. the 189-m, 400 mm Grey Cast Iron pipe group installed in 1951, and the 582-m, 250 mm Grey Cast Iron pipe group installed in 1952, have no breaks recorded during the period between 1987 and 2001.

Table 4-1 Moncton Water Main Data Inconsistency

Whole Water Main Network			Partial Water Main Network	
Material	Length(m)	Number of Breaks	Length(m)	Number of Breaks
Cast iron	199,457	2,580	107,507	1,392
A.C.		2		
Asbestos	12,439	32	6,578	25
Blue Brute		3		
Concrete	30,149	2	12,381	1
Copper	537	40		
Ductile	139,825	50	43,313	215
Galvanized		7		
Hyprescon		9		
Lead		10		
PVC	128,375	4	3,091	19
Steel		2		
Unknown	7,028	63		
Total	517,811	2,804	172,870	1,652

Table 4-2 Water Main Data Available for Analysis

Data	Quebec	Moncton
Pipe Material	Yes	Yes
Pipe Diameter	Yes	Yes
Pipe Length	Yes	Yes
Year of Installation/Pipe Age	Yes	Yes
Pipe Depth	Yes	No
Breaks History of Individual Pipes	Yes	Yes
Type of Breaks	Yes	Yes
GIS	Yes	Partial
Soil	No	Partial
Cathodic Protection for Metallic Pipes	No	No
Pavement	No	Partial
Replacement Records	No	No
Other Operation/Maintenance Records (Pressure, Flushing)	No	No

Table 4-3 Number of Breaks Before and After Filtering

Pipe Material	Prior to Filtering	After Filtering	Percent Filtered (%)
Grey Cast Iron Pipes	780	755	3
Ductile Iron Pipes with Lining	301	289	4
Ductile Iron Pipes without Lining	329	314	5
PVC	306	161	47
Hyprescon	69	62	10
Total	1,785	1,581	11

Table 4-4 Grey Cast Iron Pipes Number of Breaks Breakdown (Partial)

Diameter (mm)		100	100	100	100	100	100	100	100	100	150	150	150	150	150	150
Year Installed		1954	1955	1958	1959	1960	1961	1963	1964	1965	1940	1951	1952	1953	1954	1955
Total Length (m)		455	78	48	92	48	99	259	575	187	305	1293	2436	712	11022	4115
Total number of breaks by year	1987								1			1	1		5	
	1988							2				2			7	1
	1989	1							2				1	1	8	3
	1990	1				1						2	1		4	
	1991						1		1			1		1	8	6
	1992							1	1		2	2	1		5	3
	1993											1	1		9	3
	1994								2				2	1	5	
	1995												1		6	2
	1996											1	2		7	1
	1997	1					1		1						2	3
	1998												2		7	
	1999	1											2		11	
	2000														9	2
	2001		1			1									2	
Total	755	4	1	0	0	2	2	3	8	0	2	10	14	3	95	24

Table 4-5 Number of Breaks for Different Groups of Pipes

Material	Diameter	Installation Period	Total Lengths (Km)	No. of Breaks by Year 1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	Total
Grey Cast Iron	**All**	**All**	**130**	**45**	**59**	**62**	**50**	**58**	**59**	**68**	**63**	**48**	**39**	**53**	**54**	**40**	**40**	**17**	**755**
	All	1950s	59	22	28	34	24	31	24	36	21	20	23	25	18	21	24	7	358
	All	1960s	64	23	30	27	25	26	31	31	40	25	15	27	36	18	13	10	377
	All	1970s	5	0	1	1	0	1	2	1	1	2	1	1	0	1	1	0	13
	150mm	1950s	35	16	18	20	16	26	20	28	15	15	17	14	14	16	16	5	256
	150mm	1960s	37	15	22	19	16	23	20	27	26	18	11	17	31	16	10	8	279
	150mm	1970s	3	0	1	1	0	1	2	1	1	2	1	1	0	1	1	0	13
Ductile Iron(Not Lined)	**All**	**All**	**67**	**32**	**26**	**22**	**28**	**17**	**24**	**22**	**30**	**13**	**22**	**27**	**17**	**14**	**18**	**2**	**314**
	All	1960s	20	15	10	12	11	8	14	8	9	2	8	10	5	4	8	2	126
	All	1970s	47	17	16	10	17	9	10	14	21	10	14	17	12	10	10	0	187
	150mm	1960s	10	8	9	9	7	6	10	5	6	2	5	8	3	3	6	2	89
	150mm	1970s	23	9	12	10	10	7	7	10	15	8	13	9	8	6	8	0	132
Ductile Iron-Lined	**All**	**All**	**70**	**17**	**22**	**26**	**17**	**19**	**23**	**24**	**27**	**17**	**16**	**21**	**17**	**25**	**12**	**6**	**289**
	All	1970s	25	6	10	9	4	8	9	13	10	2	6	7	3	11	5	0	103
	All	1980s	45	11	12	17	13	11	14	11	17	15	10	14	14	14	7	6	186
	150mm	1970s	13	5	10	8	3	8	5	5	8	2	5	4	2	7	3	0	75
	150mm	1980s	25	7	7	9	10	3	10	10	16	13	7	9	7	11	5	4	128

Table 4-6 Grey Cast Iron Pipes Total No. of Breaks (1987-2001) by Individual Pipes (Partial)

Total Number of Breaks from 1987 to 2001	Pipe ID	Length (m)	Type of Break	Date of Break	Date of Installation	Material	Diameter (mm)
1	10398	29	circumferential	1990-10-17	1954-1-1	Grey Cast Iron	300
1	11973	12	Longitudinal	1993-1-25	1954-1-1	Grey Cast Iron	300
1	13110	22	circumferential	1998-1-23	1954-1-1	Grey Cast Iron	300
2	9976	100	circumferential	1987-1-29	1955-1-1	Grey Cast Iron	300
	9976	100	circumferential	1993-2-27	1955-1-1	Grey Cast Iron	300
	10444	58	circumferential	1994-2-19	1959-1-1	Grey Cast Iron	300
	10444	58	Joint	1994-8-22	1959-1-1	Grey Cast Iron	300
3	10444	58	circumferential	1999-3-2	1959-1-1	Grey Cast Iron	300
4	8859	148	circumferential	1987-10-25	1960-1-1	Grey Cast Iron	300
	8859	148	circumferential	1992-3-26	1960-1-1	Grey Cast Iron	300
	8859	148	Longitudinal	1994-2-12	1960-1-1	Grey Cast Iron	300
	8859	148	Longitudinal	1995-2-10	1960-1-1	Grey Cast Iron	300
1	6427	99	circumferential	1997-3-3	1963-1-1	Grey Cast Iron	300
1	10867	108	circumferential	1997-11-18	1963-1-1	Grey Cast Iron	300
1	6845	27	circumferential	2000-3-19	1964-1-1	Grey Cast Iron	300
	5844	147	circumferential	1987-10-6	1961-1-1	Grey Cast Iron	400
2	5844	147	circumferential	1997-3-12	1961-1-1	Grey Cast Iron	400
1	6838	51	circumferential	1992-12-12	1963-1-1	Grey Cast Iron	400
1	5896	90	circumferential	1990-3-26	1964-1-1	Grey Cast Iron	400
5	8159	99	circumferential	1989-9-5	1959-1-1	Grey Cast Iron	600
	8159	99	circumferential	1993-3-26	1959-1-1	Grey Cast Iron	600
	8159	99	Perforation	1996-11-22	1959-1-1	Grey Cast Iron	600
	8159	99	Fire hydrant joint	1997-10-9	1959-1-1	Grey Cast Iron	600
	8159	99	Fire hydrant joint	1997-10-22	1959-1-1	Grey Cast Iron	600

Table 4-7 Pipe Age at Break for Grey Cast Iron Pipes (Partial)

			Year															
			1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	
			Pipe Ages from 1987 to 2001															
Diameter (mm)	**Year of Installation**	**Length (m)**	***37***	***38***	***39***	***40***	***41***	***42***	***43***	***44***	***45***	***46***	***47***	***48***	***49***	***50***	***51***	**Sub Total of Number of Breaks**
150	1951	1,293	1	2		2	1	2	1			1						9
200	1951	290												1				1
300	1951	166																0
400	1951	189																0
	Sub Total	1,937	1	2	0	2	1	2	1	0	0	1	0	1	0	0	0	10
			36	***37***	***38***	***39***	***40***	***41***	***42***	***43***	***44***	***45***	***46***	***47***	***48***	***49***	***50***	
150	1952	2,436	1		1	1		1	1	2	1	2		2	2			14
200	1952	1,953	1				1			1	1	3				1		8
250	1952	582																0
300	1952	132			2	1												3
350	1952	81																0
400	1952	115																0
600	1952	18																0
900	1952	47																0
	Sub Total	5,365	2	0	3	2	1	1	1	3	2	5	0	2	2	1	0	25

4.4 Descriptive Statistics of Quebec Water Mains

The descriptive statistics can provide details on the water main network itself, and the characteristics about pipe material, breaks type, length, diameter, time of installation, and break rate, which are useful for further analysis on specific groups of pipes.

4.4.1 Pipe Length by Material

Figure 4-1 shows that in Quebec's water main network, the Grey Cast Iron pipe group is of 30% of total network length. The PVC, Ductile Iron (Lined) and Ductile (Not Lined) pipes have similar total length in the network .

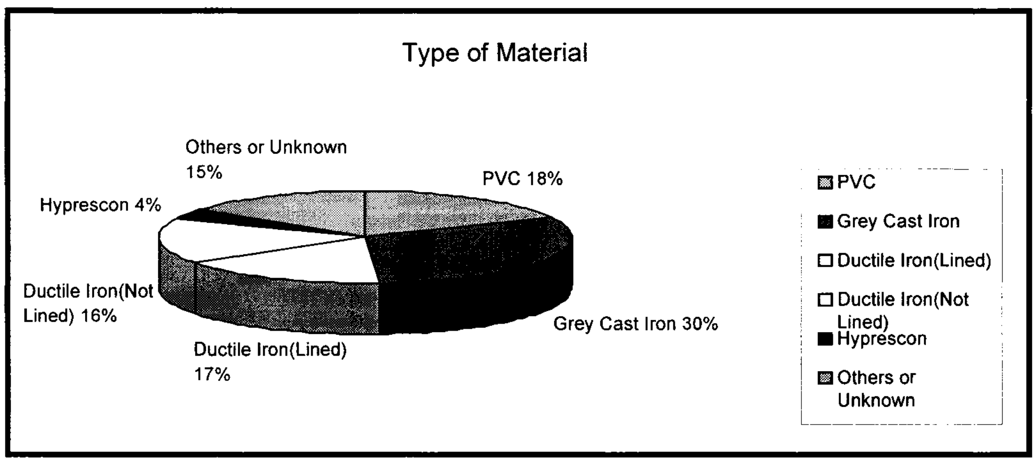

Figure 4-1 Pipe Length by Material

4.4.2 Pipe Length by Diameter

Figure 4-2 shows that the majority (71%) water mains of the network are of pipe sizes between 150 mm and 200 mm. Less than 10% pipes are of pipe size more than 350 mm.

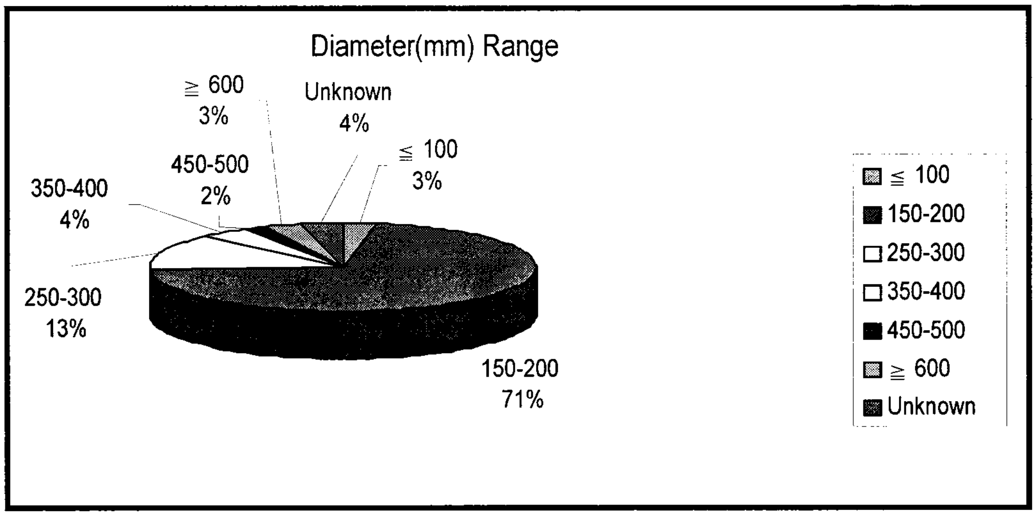

Figure 4-2 Pipe Length by Diameter

4.4.3 Breaks by Type

Figure 4-3 shows that about 80% breaks in Quebec is of circumferential type. The subtotal number of breaks of longitudinal, circumferential, and perforation types is more than 90% of the total number of breaks.

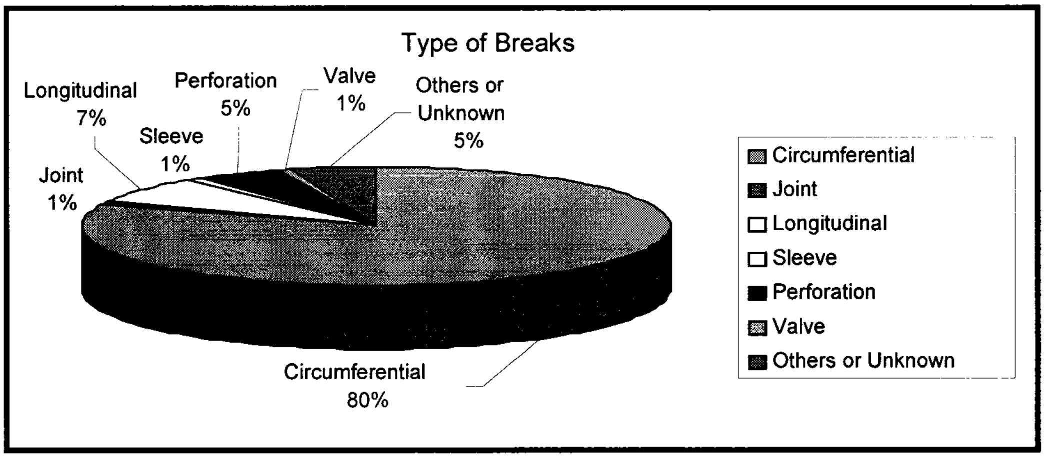

Figure 4-3 Type of Breaks

4.4.4 Breaks by Age

The numbers of breaks are totaled according to the ages at which a pipe or pipe group had breaks between 1987 and 2001. For example, according to Table 4-7, for the 1,293-m, 150mm Grey Cast Iron pipe group installed in 1951, between 1987 and 2001, there are 1, 2, 2, 1, 2, 1,1 numbers of breaks at the ages 37, 38, 40,41,42,46 respectively. So, 1, 2, 2, 1, 2, 1, 1 number of breaks are put under the ages 37, 38, 40,41,42,46 respectively. The 150 mm Grey Cast Iron pipe group installed in 1952 has 1, 1, 1, 1, 1, 2, 1, 2, 2, 2 numbers of breaks that occurred when these pipes had ages of 36, 38, 39, 41, 42, 43, 44, 45, 47, 48 years respectively. For these two pipe groups, under the age of 38 years, there are 2 plus 1 total 3 breaks. Using the same principle, other numbers of breaks occurred at the same ages of different pipe groups are added.

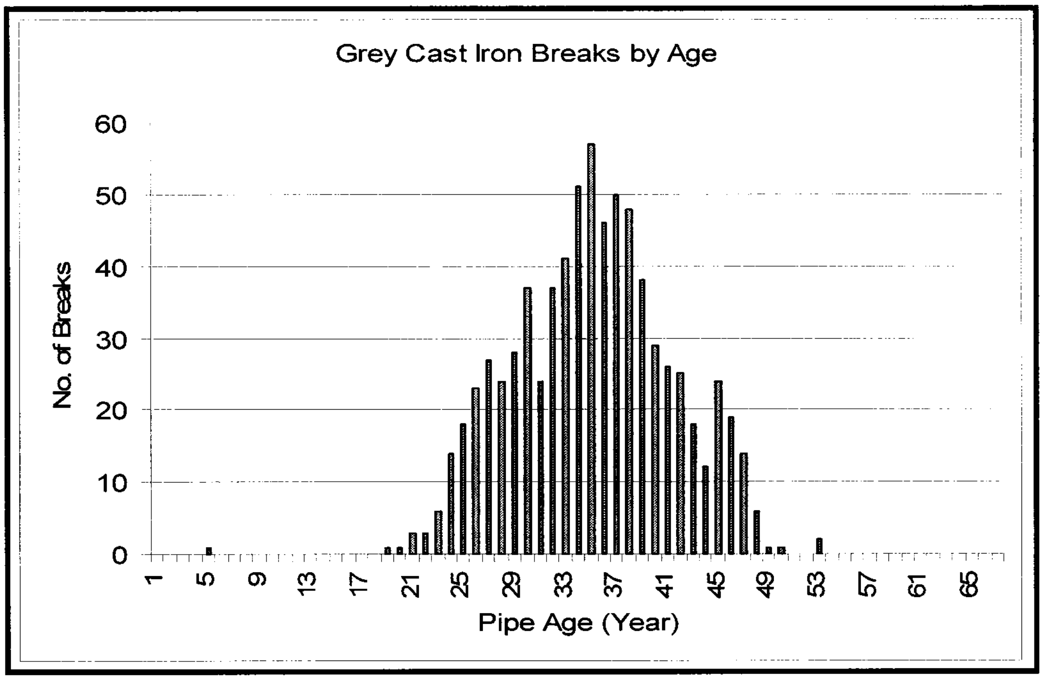

Figure 4-4 Grey Cast Iron Pipe Breaks by Age

Figure 4-4 shows the total number of breaks of the Grey Cast Iron pipes in Quebec by age. It shows that in the Quebec data, for all the Grey Cat Iron pipes, between 1987 and 2001, all the breaks occurred when the pipes are of ages between 20 and 50 years. However, it does not lead to the conclusion that pipes or pipe groups of older ages may have fewer or more breaks when compared with other pipes or pipe groups that had breaks from 1987 to 2001, since the number of breaks does not represent a life cycle case of all the Grey Cast iron pipes. For example, pipes that had breaks at the age of 51 years seem to have fewer breaks compared to others in this figure because there are only very few pipes of small lengths that experienced breaks at the ages of 51. In other words, it may not be possible to determine the relationship between the total number of breaks and the pipe ages at which the pipes experienced breaks. Cameron (2005) has reported similar figures for the water main network of Edmonton.

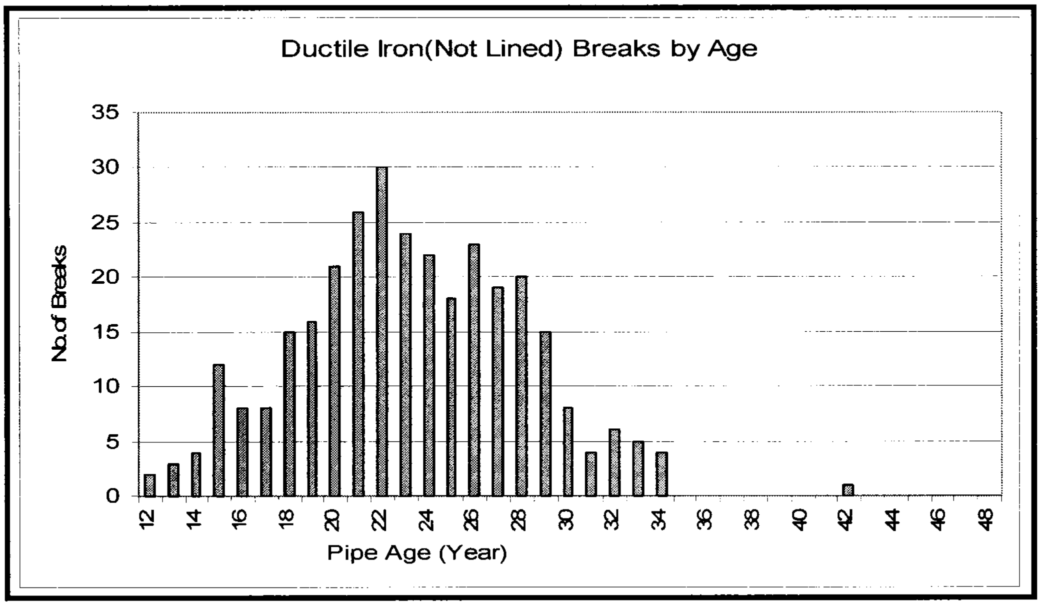

Figure 4-5 Ductile Iron (Not Lined) Pipe Breaks by Age

Figure 4-5 is developed using the same principle as that of the Grey Cast Iron pipes mentioned above. It shows the total number of breaks of the Ductile Iron (Not Lined) pipes by age. It shows that in the Quebec data, for all the Ductile Iron (Not Lined) pipes, between 1987 and 2001, all the breaks occurred when the pipes are of ages between 12 and 34 years.

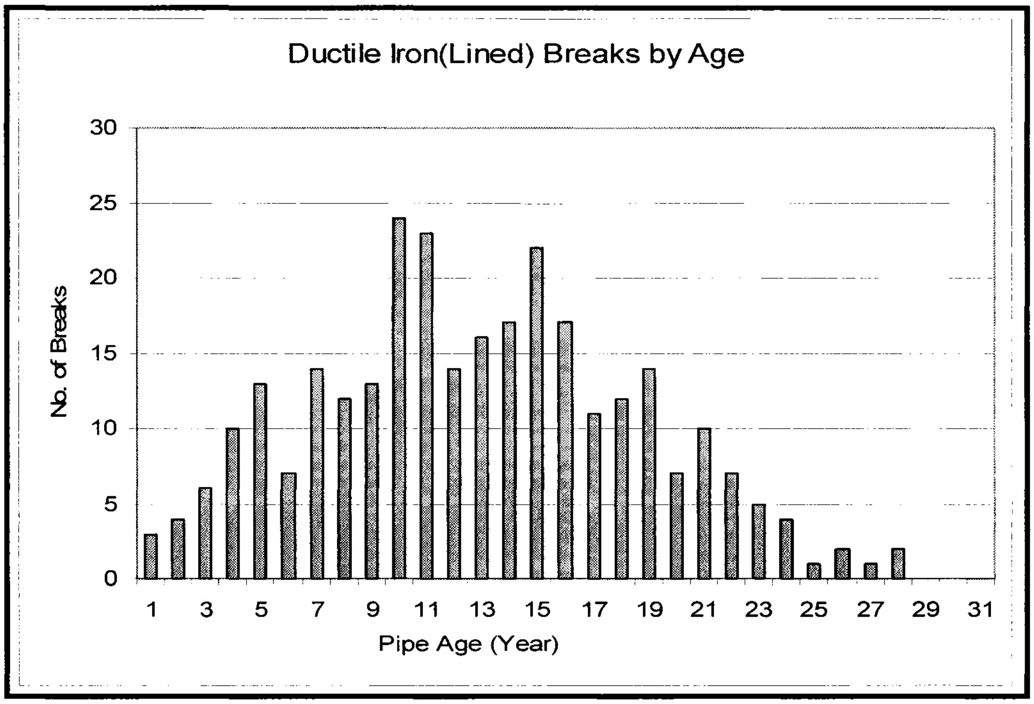

Figure 4-6 Ductile Iron (Lined) Pipe Breaks by Age

Figure 4-6 is also developed using the same principle as that of the Grey Cast Iron pipes mentioned above. It shows the total number of breaks of the Ductile Iron (Lined) pipes by age. It shows that in the Quebec data, for all the Ductile Iron (Lined) pipes, between 1987 and 2001, all the breaks occurred when the pipes are of ages between 1 and 28 years.

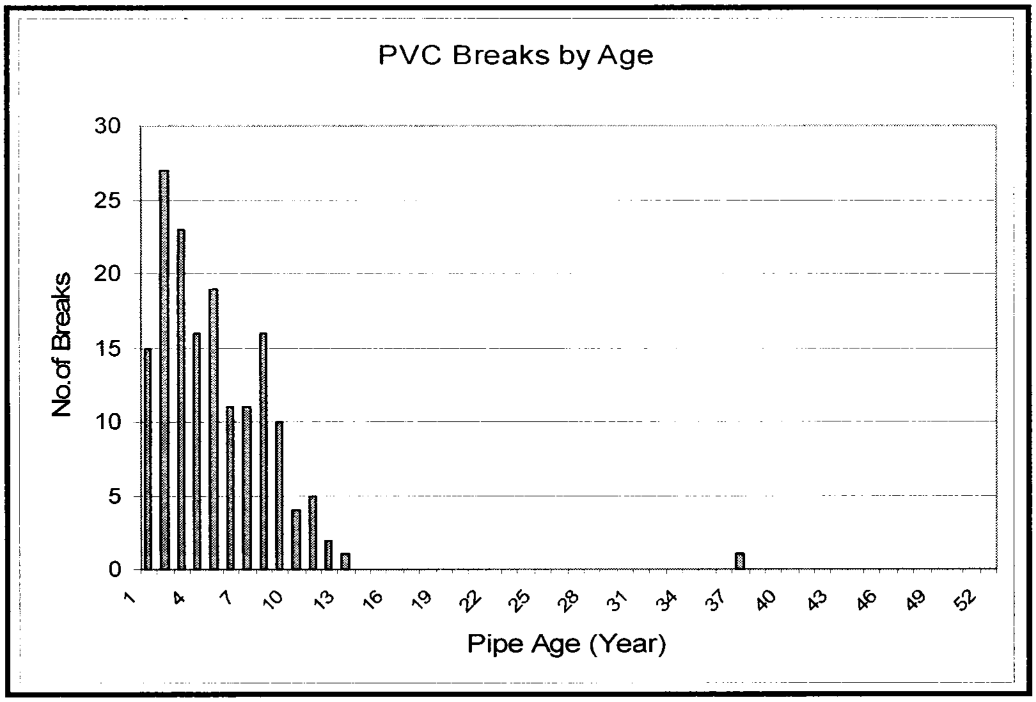

Figure 4-7 PVC Pipe Breaks by Age

Figure 4-7 shows the total number of breaks of the PVC pipes by age. It shows that in the Quebec data, for all the PVC pipes, between 1987 and 2001, all the breaks occurred when the pipes are of ages between 1 and 14 years.

4.4.5 Breaks by Material

Figure 4-8 shows that according to the data from Quebec the majority of breaks are on Grey Cast Iron pipes (42%), while the PVC, Ductile Iron (Lined) and Ductile (Not Lined) pipes in the network have fewer breaks, and have similar percentages of total number of breaks.

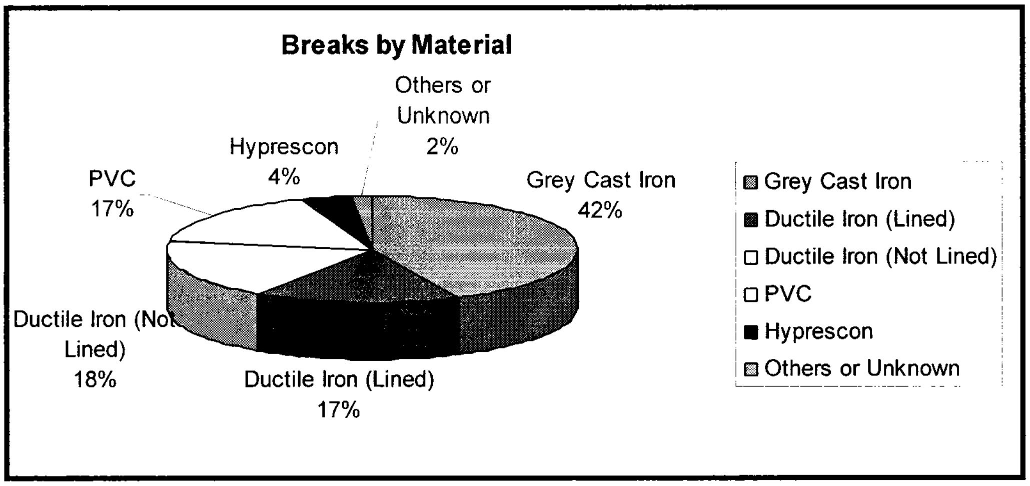

Figure 4-8 Pipe Breaks by Material

4.4.6 Pipe Length by Year of Installation and by Material

Figure 4-9 illustrates the lengths of Grey Cast Iron by year of installation. The 1950s and 1960s are two decades in which more Grey Cast Iron water mains were installed.

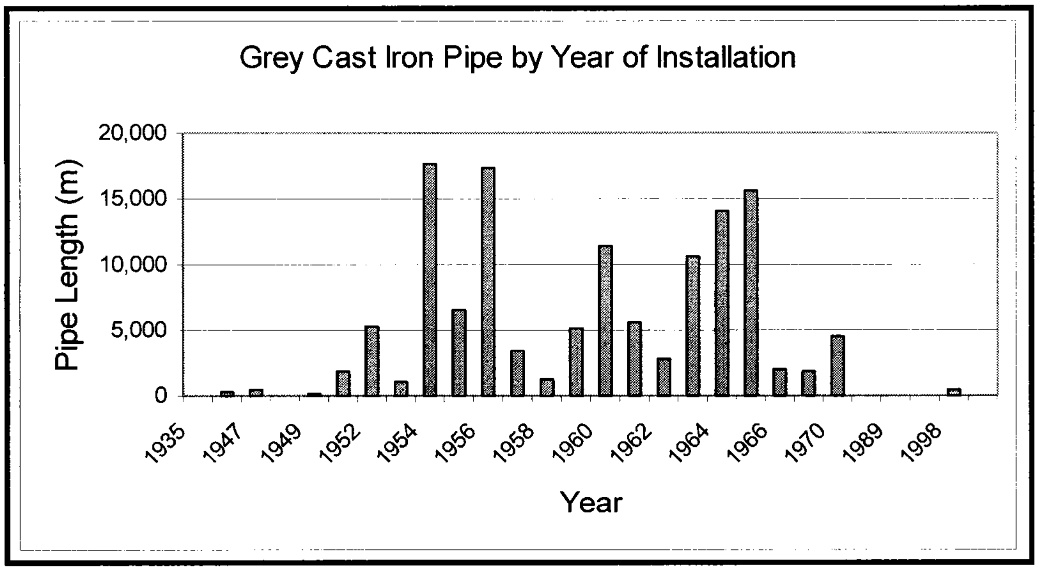

Figure 4-9 Grey Cast Iron Pipe Length by Year of Installation

Figure 4-10 shows that the majority of Ductile Iron (Not Lined) pipes were installed in the 1960s and 1970s. In average, about 6 km of pipes were installed every year from 1969 to 1976.

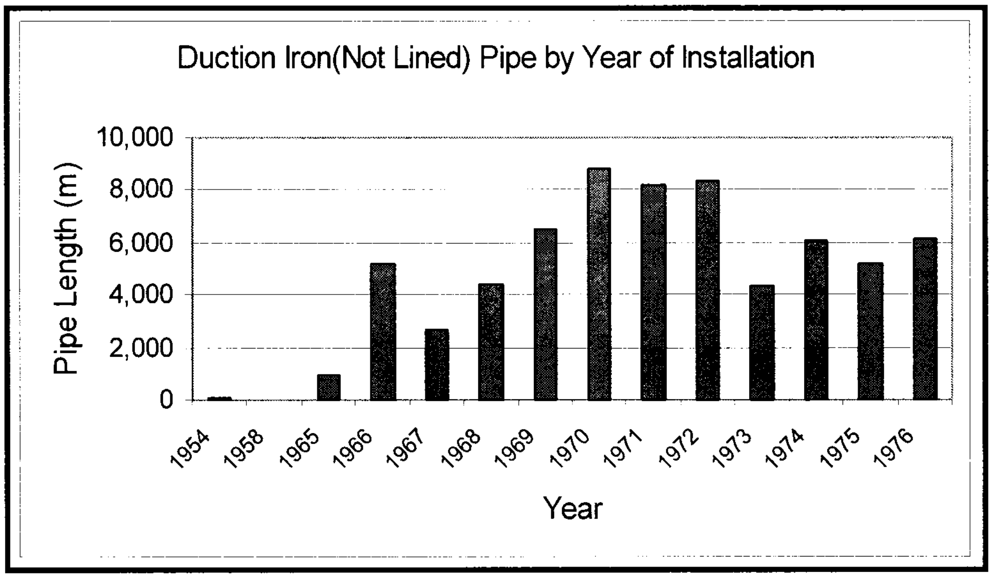

Figure 4-10 Ductile Iron (Not Lined) Pipe Length by Year of Installation

Figure 4-11 shows that most of the Ductile Iron (Lined) Pipes were installed in the 1970s and 1980s in Quebec.

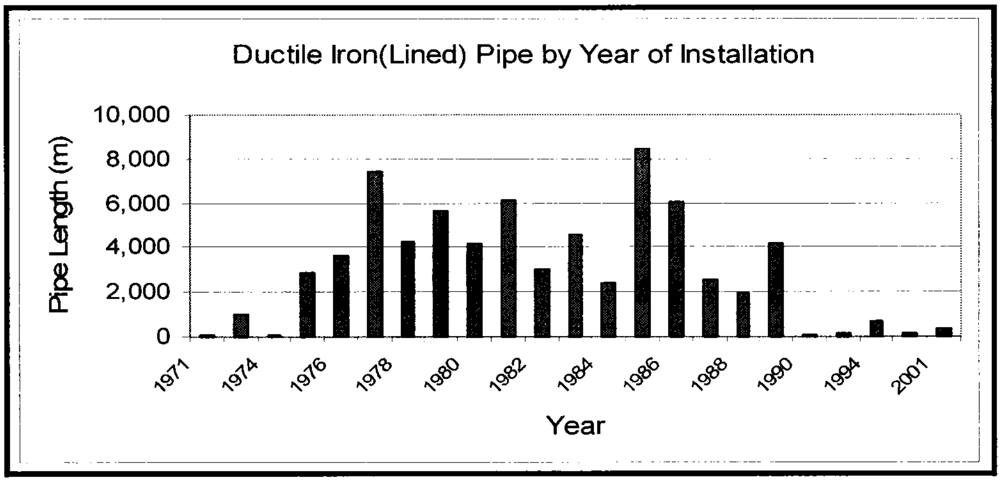

Figure 4-11 Ductile Iron (Lined) Pipe Length by Year of Installation

4.5 Distributions of Breaks and Lengths by Pipe Group

Two percentages (Refer to Equations 4-1 and 4-2) have been compared to check the distribution of breaks in Quebec by pipe group and length. The pipe groups are formed according to pipe material, diameter, year and decade of installation.

Percentage 1: % of Total No. of Breaks in 15 Years

$$\frac{\text{Subtotal number of breaks for a pipe group}}{\text{Total number of breaks by material or network}} \times 100\% \qquad 4\text{-}1$$

Percentage 2: % of Total Length

$$\frac{\text{Subtotal length for a pipe group}}{\text{Total length by material or network}} \times 100\% \qquad 4\text{-}2$$

Table 4-8 shows the distributions of numbers of breaks and pipe lengths by material. For example, in 15 years between 1987 and 2001, 755 breaks occurred on the Grey Cast Iron pipes that are 47.75% of the total 1581 breaks, while the 129,953 m of the Grey Cast Iron pipes are 36.61% of the total pipe length, 354,495 m. It should be noted the total length and the total number of breaks consist of those of the Grey Cast Iron, Ductile Iron Lined and Not Lined, PVC, and Hyprescon pipes only.

Table 4-8 Distributions of Breaks and Lengths by Material

Pipe Material	% of Total Number of Breaks (Percentage 1)	% of Total Length (Percentage 2)	Pipe Length (m)	Total Number of Breaks
PVC	10.18	20.59	73,098	160
Ductile Iron(Lined)	18.28	19.69	69,887	289
Ductile Iron(Not Lined)	19.86	18.87	66,977	314
Grey Cast Iron	47.75	36.61	129,953	755
Hyprescon	3.92	4.24	15,050	62
Total	100	100	354,965	1,581

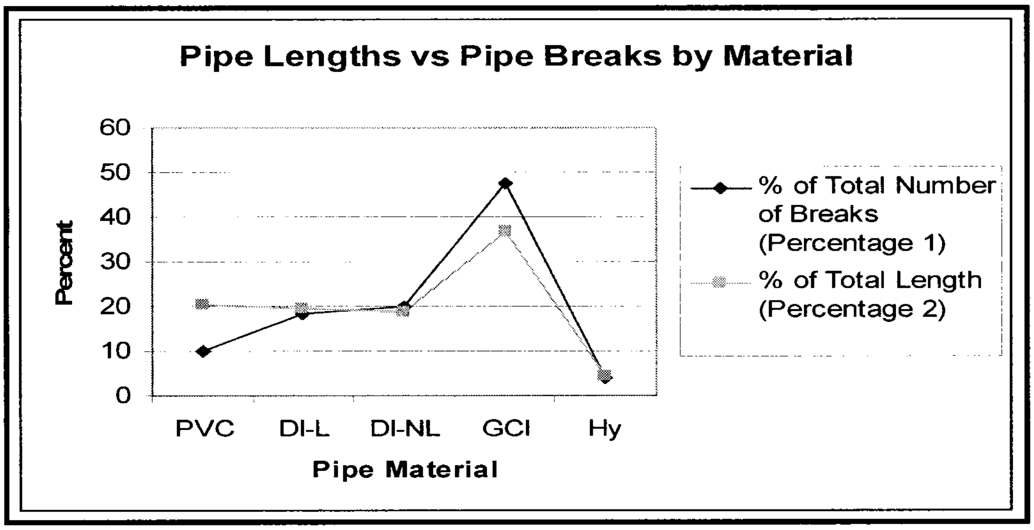

Figure 4-12 Percent of Total Number of Breaks vs Percent of Total Length by Material

Figure 4-12 shows the two percentages of Table 4-8 for comparison. The two percentages of the Ductile Iron Lined and Not Lined, Hyprescon pipes are close. The Grey Cast Iron pipes have the largest percentages in the subtotal of number of breaks and length against the total number of breaks and the total length of the network. The PVC pipes have a lower percentage on the subtotal number of breaks versus the total number of breaks of the network than the percentage on the subtotal length versus the total length of the network. Figure 4-12 may indicate that more breaks occurred for pipe groups of longer lengths in a water main network in the same period of time.

Table 4-9 shows the distributions of numbers of breaks and pipe lengths by diameter for the Grey Cast Iron pipes in Quebec. For example, in 15 years between 1987 and 2001, 553 breaks that occurred on the 150 mm Grey Cast Iron pipes are 73.25% of the total 755 breaks, while the 76,288 m of the 150 mm Grey Cast Iron pipes are 58.70% of the total length, 129,953 m.

Table 4-9 Distributions of Breaks and Lengths for GCI Pipes by Diameter

Pipe Diameter (mm)	100	150	200	250	300	350	400-900	Total
Total Number of Breaks (1987-2001)	23	553	107	45	18	0	9	755
Total Length (m)	2,268	76,288	23,621	11,594	6,267	1,564	8,351	129,953
% of Total Number of Breaks (Percentage 1)	3.05	73.25	14.17	5.96	2.38	0.00	1.19	100.00
% of Total Length (Percentage 2)	1.74	58.70	18.18	8.92	4.82	1.20	6.43	100.00

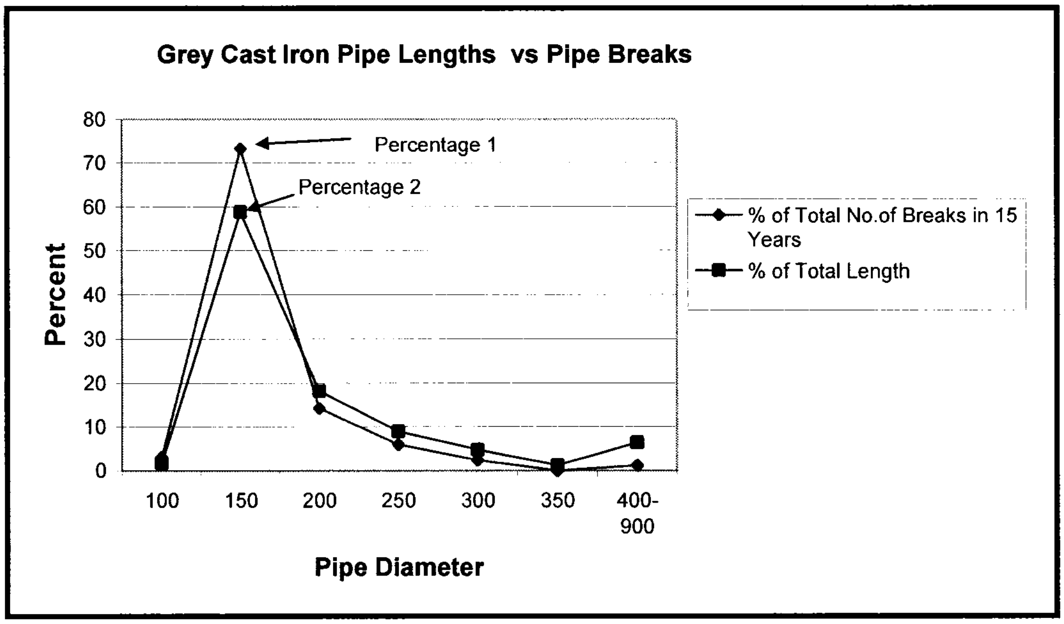

Figure 4-13 Grey Cast Iron Pipe Lengths versus Pipe Breaks by Pipe Diameter

Figure 4-13 shows the two percentages of Table 4-9 for comparison for the Grey Cast Iron pipes by diameter. It shows that the longer the length of a group of pipes by diameter, the more breaks occurred on this group of pipes compared to others.

Table 4-10 shows the distributions of numbers of breaks and pipe lengths by diameter for the Ductile Iron (Not Lined) pipes in Quebec. For example, in 15 years between 1987 and 2001, 221 breaks that occurred on the 150 mm Ductile Iron (Not Lined) pipes are 70.38% of the total 314 breaks, while the 33,340 meters of the 150 mm Ductile Iron (Not Lined) pipes are 49.78% of the total length, 66,977 meters.

Table 4-10 Distributions of Breaks and Lengths for DI-NL Pipes by Diameter

Pipe Diameter (mm)	25-75	100	150	200	250	300	350	400-900	Total
Total Number of Breaks (1987-2001)	0	5	221	65	12	8	0	3	314
Total Length (m)	179	628	33,340	14,266	4,781	5,894	668	7,221	66,977
% of Total Number of Breaks (Percentage 1)	0.00	1.59	70.38	20.70	3.82	2.55	0.00	0.96	100
% of Total Length (Percentage 2)	0.27	0.94	49.78	21.30	7.14	8.80	1.00	10.78	100

Figure 4-14 shows the two percentages of Table 4-10 for comparison for the Ductile Iron (Not Lined) pipes by diameter. It shows that the longer the length of a group of pipes by diameter, the more breaks occurred on this group of pipes compared to others.

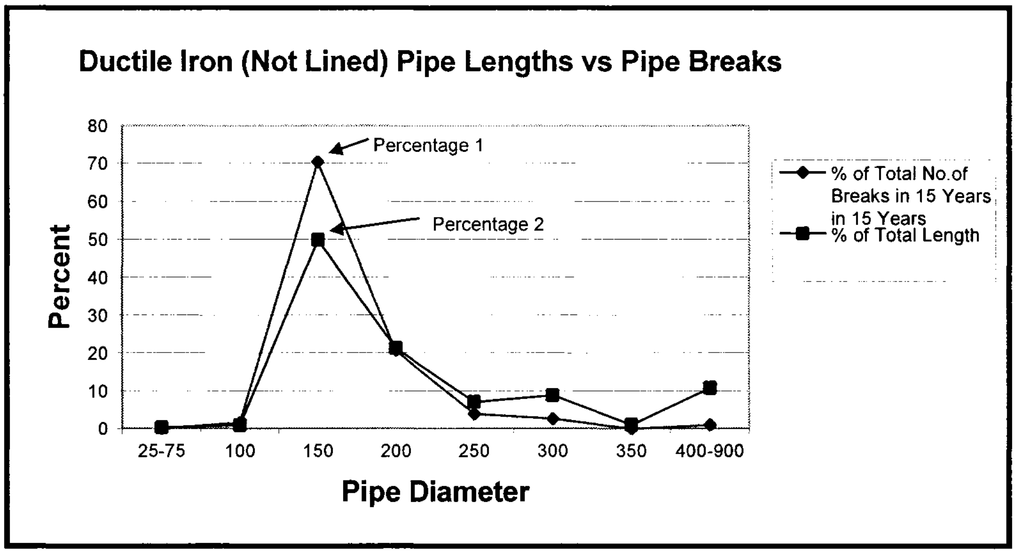

Figure 4-14 DI (Not Lined) Pipe Lengths versus Pipe Breaks by Pipe Diameter

Table 4-11 Distributions of Breaks and Lengths for DI-L Pipes by Diameter

Pipe Diameter (mm)	25-75	100	150	200	250	300	350	400-900	Total
Total Number of Breaks (1987-2001)	8	9	207	46	12	5	0	2	289
Total Length (m)	742	992	38,256	13,680	6,332	2,720	713	6,452	69,887
% of Total Number of Breaks (Percentage 1)	2.77	3.11	71.63	15.92	4.15	1.73	0.00	0.69	100
% of Total Length (Percentage 2)	1.06	1.42	54.74	19.57	9.06	3.89	1.02	9.23	100

Table 4-11 shows the distributions of numbers of breaks and pipe lengths by diameter for the Ductile Iron (Lined) pipes in Quebec. For example, in 15 years between 1987 and 2001, 207 breaks that occurred on the 150 mm Ductile Iron (Lined) pipes are 71.63% of the total 289 breaks, while the 38,256 m of the 150 mm Ductile Iron (Lined) pipes are 54.74% of the total length, 66,887 m.

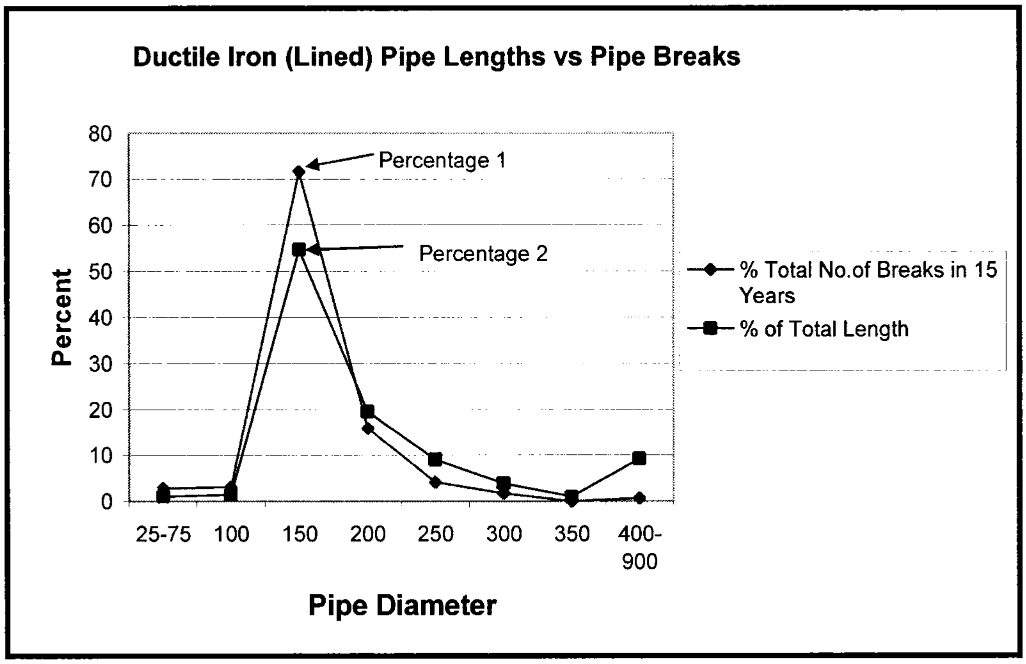

Figure 4-15 DI (Lined) Pipe Lengths versus Pipe Breaks by Pipe Diameter

Figure 4-15 shows the two percentages of Table 4-11 for comparison for the Ductile Iron (Lined) pipes by diameter. It shows that the longer the length of a group of pipes by diameter, the more breaks occurred on this group of pipes compared to others.

Table 4-12 shows the distributions of numbers of breaks and pipe lengths by diameter for the PVC pipes in Quebec. For example, in 15 years between 1987 and 2001, 116 breaks that occurred on the 150 mm PVC pipes are 72.50% of the total 160 breaks, while the 37,910 m of the 150 mm PVC pipes are 52.20% of the total length, 73,098 m.

Table 4-12 Distributions of Breaks and Lengths for PVC Pipes by Diameter

Pipe Diameter (mm)	100	150	200	250	300	350	400-900	Total
Total Number of Breaks (1987-2001)	0	116	31	6	4	0	3	160
Total Length (m)	530	37,910	16,121	6,019	4,020	299	7,730	73,098
% of Total Number of Breaks (Percentage 1)	0.000	72.500	19.375	3.750	2.500	0.000	1.875	100
% of Total Length (Percentage 2)	0.729	52.197	22.196	8.287	5.534	0.412	10.643	100

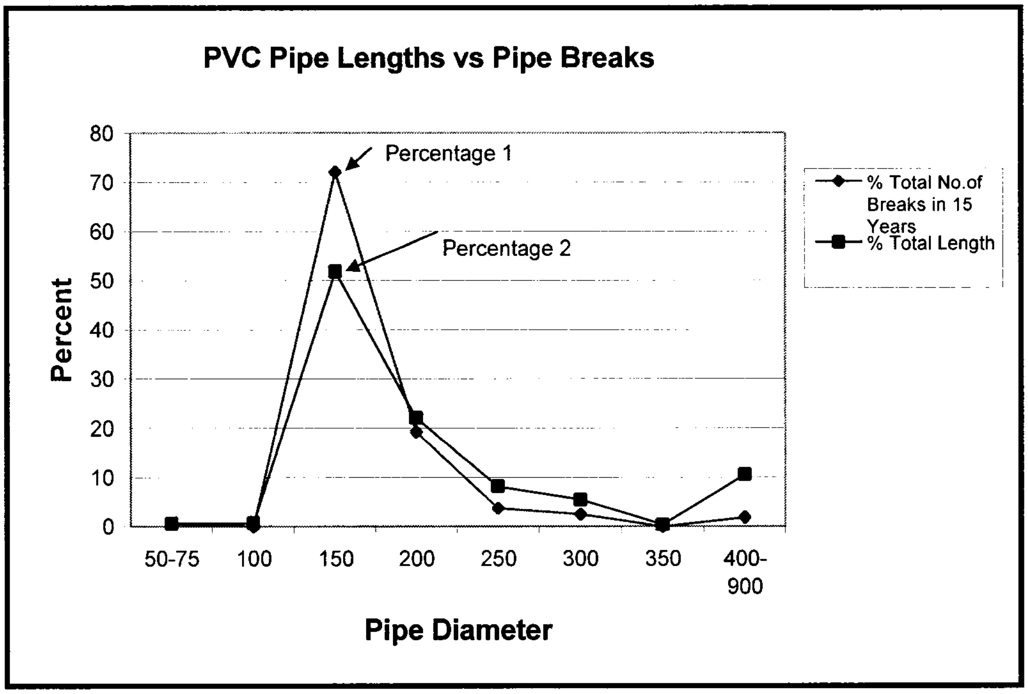

Figure 4-16 PVC Pipe Lengths versus Pipe Breaks by Pipe Diameter

Figure 4-16 shows the two percentages of Table 4-12 for comparison for the PVC pipes by diameter. It shows that the longer the length of a group of pipes by diameter, the more breaks occurred on this group of pipes compared to others.

Table 4-13 shows the distributions of numbers of breaks and pipe lengths by diameter for the Hyprescon pipes in Quebec. For example, in 15 years between 1987 and 2001, 52 breaks that occurred on the 150 mm Hyprescon pipes are 83.87% of the total 62 breaks, while the 8,144 m of the 150 mm Hyprescon pipes are 54.11% of the total length, 15,050 m.

Table 4-14 shows the distributions of numbers of breaks and pipe lengths by year of installation for the Grey Cast Iron, Ductile Iron (Not Lined). Ductile Iron (Lined) pipes. For example, in 15 years between 1987 and 2001, 129 breaks that occurred on the Grey Cast Iron pipes installed in 1954 are 17.09% of total 755 breaks, while the 17,593 m of the Grey Cast Iron pipes installed in 1954 are 13.55% of the total Grey Cast Iron pipe length, 129,953 m.

Figure 4-17 shows the two percentages of Table 4-13 for comparison for the Hyprescon pipes by diameter. It shows that the longer the length of a group of pipes by diameter, the more breaks occurred on this group of pipes compared to others.

Table 4-13 Distributions of Breaks and Lengths for Hyprescon Pipes by Diameter

Pipe Diameter (mm)	25-75	100	150	200	250	300	350	400-900	Total
Total Number of Breaks (1987-2001)	0	0	52	8	1	0	0	1	62
Total Length (m)	5	305	8,144	2,264	1,895	992	68	1,378	15,050
% of Total Number of Breaks (Percentage 1)	0.00	0.00	83.87	12.90	1.61	0.00	0.00	1.61	100
% of Total Length (Percentage 2)	0.03	2.03	54.11	15.04	12.59	6.59	0.45	9.16	100

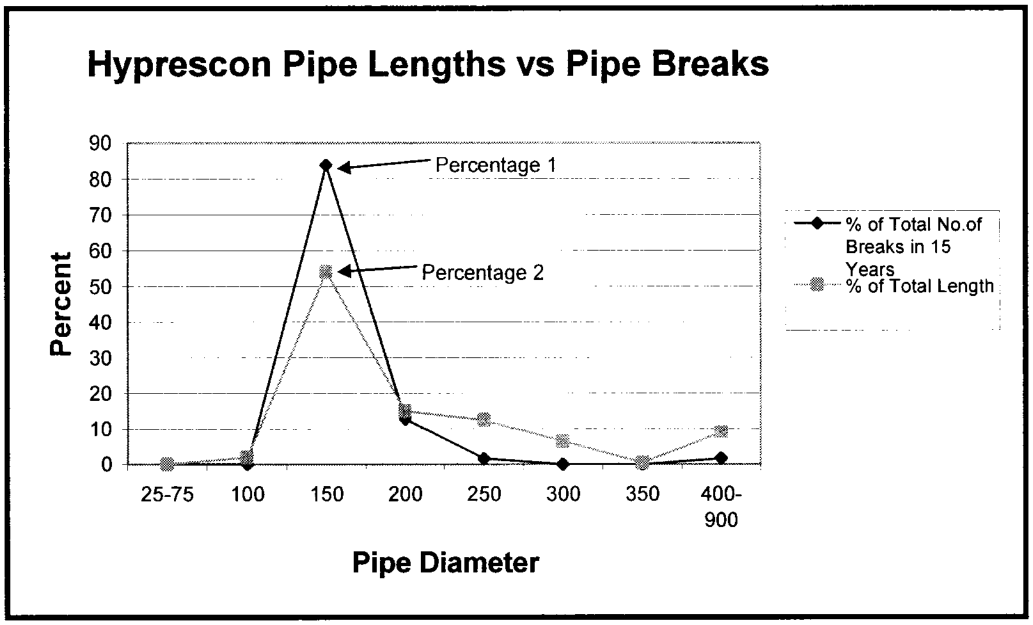

Figure 4-17 Hyprescon Pipe Lengths versus Pipe Breaks by Pipe Diameter

Table 4-14 Distributions of Breaks and Lengths by Year of Installation for GCI, DI-NL and DI-L Pipes

Grey Cast Iron Pipe					Ductile Iron (Not Lined) Pipe					Ductile Iron (Lined) Pipe				
Year of Installation	Pipe Length (m)	Total Number of Breaks (1987-2001)	% of Total Number of Breaks (Percentage 1)	% of Total Length (Percentage 2)	Year of Installation	Pipe Length (m)	Total Number of Breaks (1987-2001)	% of Total Number of Breaks (Percentage 1)	% of Total Length (Percentage 2)	Year of Installation	Pipe Length (m)	Total Number of Breaks (1987-2001)	% of Total Number of Breaks (Percentage 1)	% of Total Length (Percentage 2)
1935	25	0	0.00	0.02	1954	52	1	0.32	0.08	1971	61	0	0.00	0.09
1940	335	2	0.26	0.26	1958	24	0	0.00	0.04	1972	1,023	12	4.15	1.46
1947	423	1	0.13	0.33	1965	968	1	0.32	1.44	1974	80	0	0.00	0.11
1948	6	0	0.00	0.00	1966	5,214	20	6.37	7.78	1975	2,852	16	5.54	4.08
1949	185	3	0.40	0.14	1967	2,682	15	4.78	4.00	1976	3,659	14	4.84	5.24
1951	1,937	10	1.32	1.49	1968	4,444	32	10.19	6.63	1977	7,469	30	10.38	10.69
1952	5,365	25	3.31	4.13	1969	6,550	58	18.47	9.78	1978	4,278	8	2.77	6.12
1953	1,151	5	0.66	0.89	1970	8,793	25	7.96	13.13	1979	5,662	23	7.96	8.10
1954	17,593	129	17.09	13.55	1971	8,188	35	11.15	12.23	1980	4,148	9	3.11	5.94
1955	6,519	37	4.90	5.02	1972	8,376	44	14.01	12.51	1981	6,109	17	5.88	8.74
1956	17,276	89	11.79	13.31	1973	4,296	10	3.18	6.41	1982	3,022	22	7.61	4.32
1957	3,362	23	3.05	2.59	1974	6,091	20	6.37	9.09	1983	4,586	29	10.03	6.56
1958	1,231	4	0.53	0.95	1975	5,191	21	6.69	7.75	1984	2,429	10	3.46	3.48
1959	5,170	39	5.17	3.98	1976	6,109	32	10.19	9.12	1985	8,419	45	15.57	12.05
1960	11,410	75	9.93	8.79	Total	66,977	314	100.00	100.00	1986	6,047	25	8.65	8.65
1961	5,585	39	5.17	4.30						1987	2,550	7	2.42	3.65
1962	2,840	25	3.31	2.19						1988	1,947	11	3.81	2.79
1963	10,658	57	7.55	8.21						1989	4,172	7	2.42	5.97
1964	14,047	94	12.45	10.82						1990	54	0	0.00	0.08
1965	15,643	69	9.14	12.05						1991	146	0	0.00	0.21
1966	2,070	6	0.79	1.59						1994	679	4	1.38	0.97
1968	1,931	9	1.19	1.49						1998	118	0	0.00	0.17
1970	4,571	13	1.72	3.52						2001	378	0	0.00	0.54
1979	26	0	0.00	0.02						Total	69,887	289	100	100
1989	4	0	0.00	0.00										
1994	11	0	0.00	0.01										
1998	396	1	0.13	0.30										
2001	77	0	0.00	0.06										
Total	129,953	755	100	100										

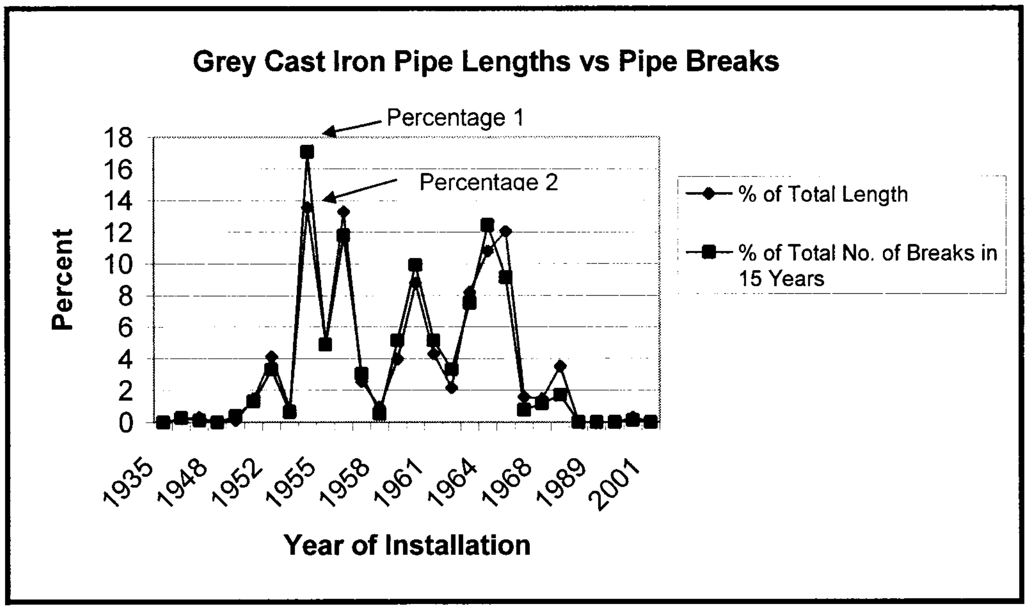

Figure 4-18 GCI Pipe Lengths versus Pipe Breaks by Year of Installation

Figure 4-18 shows the two percentages of the Grey Cast Iron pipes in Table 4-14 for comparison by year of installation. It shows that the longer the length of a group of pipes by year of installation, the more breaks occurred on this group of pipes compared to others.

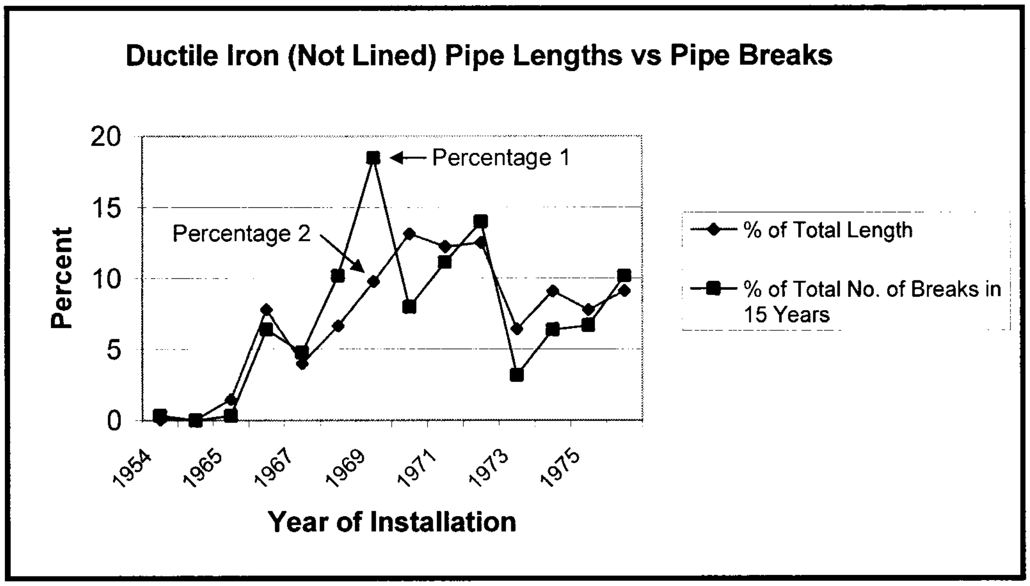

Figure 4-19 DI-NL Pipe Lengths versus Pipe Breaks by Year of Installation

Figure 4-19 shows the two percentages of the Ductile Iron (Not Lined) pipes in Table 4-14 for comparison by year of installation. It shows that the longer the length of a group of pipes by year of installation, the more breaks occurred on this group of pipes compared to others. However, this figure shows that the Ductile Iron (Not Lined) pipes installed in 1969 have a higher percentage of total breaks compared to the pipes installed in 1970 even though the latter has a larger length (8,793 m) than the former (6,550 m).

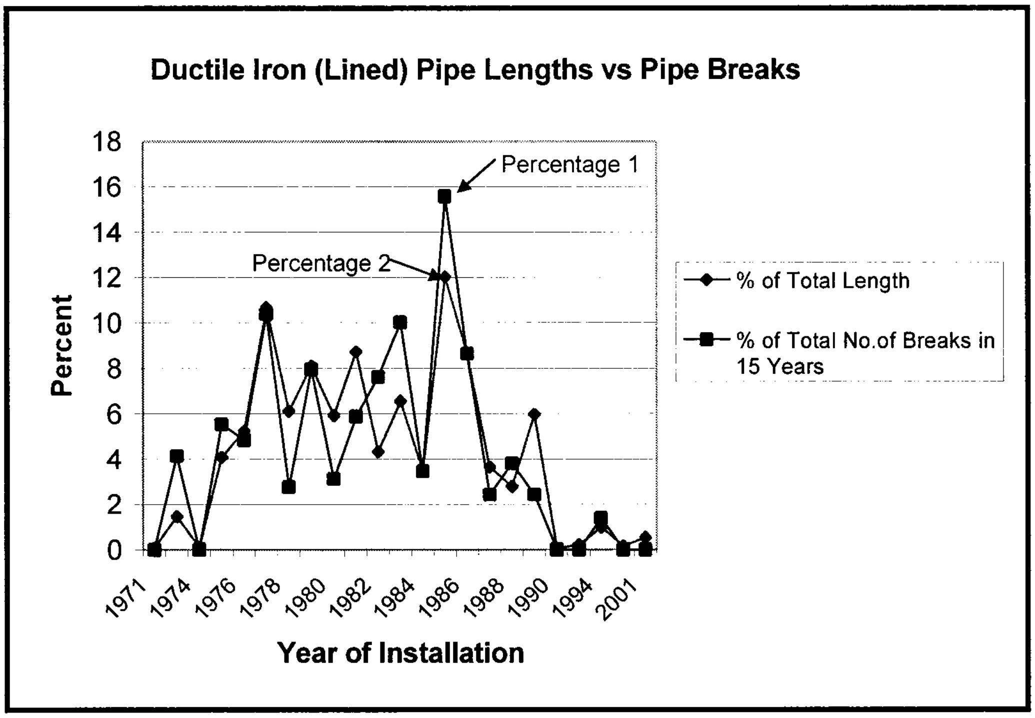

Figure 4-20 DI (Lined) Pipe Lengths versus Pipe Breaks by Year of Installation

Figure 4-20 shows the two percentages of the Ductile Iron (Lined) pipes in Table 4-14 for comparison by year of installation. It shows that the longer the length of a group of pipes by diameter, the more breaks occurred on this group of pipes compared to others. However, this figure shows that the Ductile Iron (Lined) pipes installed in 1982 have a higher percentage of total breaks compared to the pipes installed in 1981 even though the latter has a larger length (6,109 m) than the former (3,022 m).

Table 4-15 shows the distributions of numbers of breaks and pipe lengths by decade of installation for the Grey Cast Iron pipes in Quebec. For example, in 15 years between 1987 and 2001, 358 breaks that occurred on the Grey Cast Iron pipes installed in the 1950s are 47.72% of the total 755 breaks, while the 59,348 meters of the Grey Cast Iron pipes installed in the 1950s are 45.67% of the total length, 129,953 meters.

Table 4-15 Distributions of Breaks and Lengths for GCI Pipes by Decade of Installation

Decade Pipe Installed	1930s	1940s	1950s	1960s	1970s	1980s	1990s	2000s	Total
Total No. of Breaks	0	6	358	377	13	0	1	0	755
Total Length (m)	25	950	59,348	64,439	4,597	4	407	183	129,953
% of Total No. of Breaks (Percentage 1)	0.00	0.79	47.42	49.93	1.72	0.00	0.13	0.00	100
% of Total Length (Percentage 2)	0.02	0.73	45.67	49.59	3.54	0.00	0.31	0.14	100

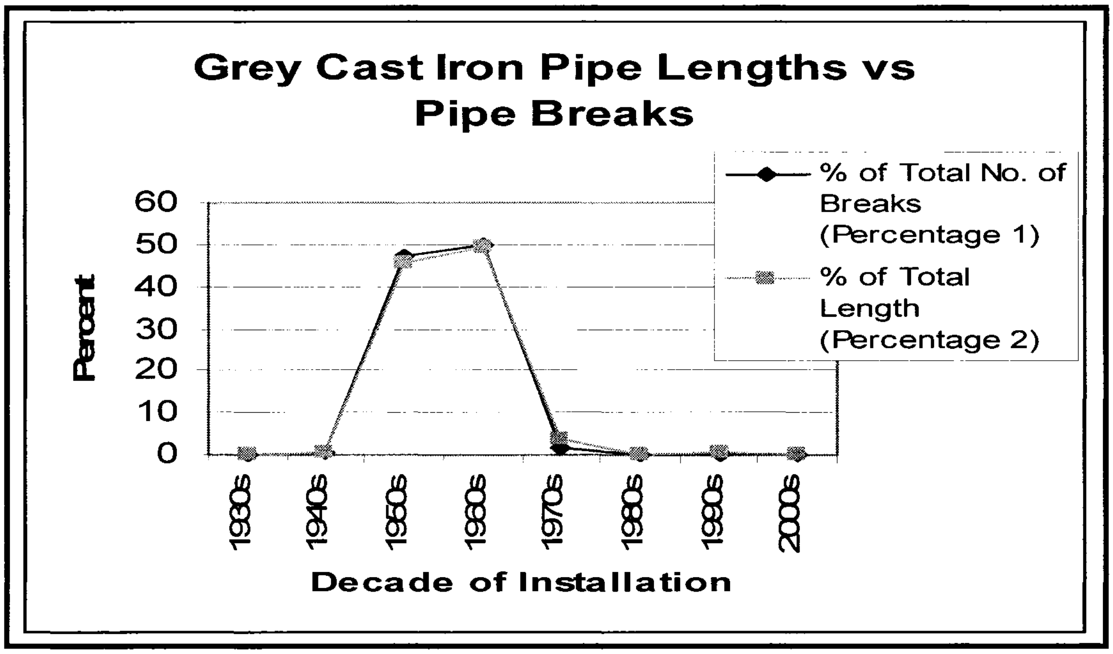

Figure 4-21 GCI Pipe Lengths versus Pipe Breaks by Decade of Installation

Figure 4-21 shows the two percentages of the Grey Cast Iron pipes in Table 4-15 for comparison by decade of installation. It shows that the longer the length of a group of pipes by diameter, the more breaks occurred on this group of pipes compared to others.

Table 4-16 shows the distributions of numbers of breaks and pipe lengths by decade of installation for the Ductile Iron (Not Lined) pipes in Quebec. For example, in 15 years between 1987 and 2001, 126 breaks that occurred on the Ductile Iron (Not Lined) pipes installed in the 1960s are 40.13% of the total 314 breaks, while the 19,587 meters of the Ductile Iron (Not Lined) pipes installed in the 1960s are 40.13% of the total length, 66,977 meters.

Table 4-16 Distributions of Breaks and Lengths for DI-NL Pipes by Decade of Installation

Decade Pipe Installed	1950s	1960s	1970s	Total
Total No. of Breaks	1	126	187	314
Total Length (m)	76	19,857	47,044	66,977
% of Total No. of Breaks (Percentage 1)	0.32	40.13	59.55	100.00
% of Total Length (Percentage 2)	0.11	29.65	70.24	100

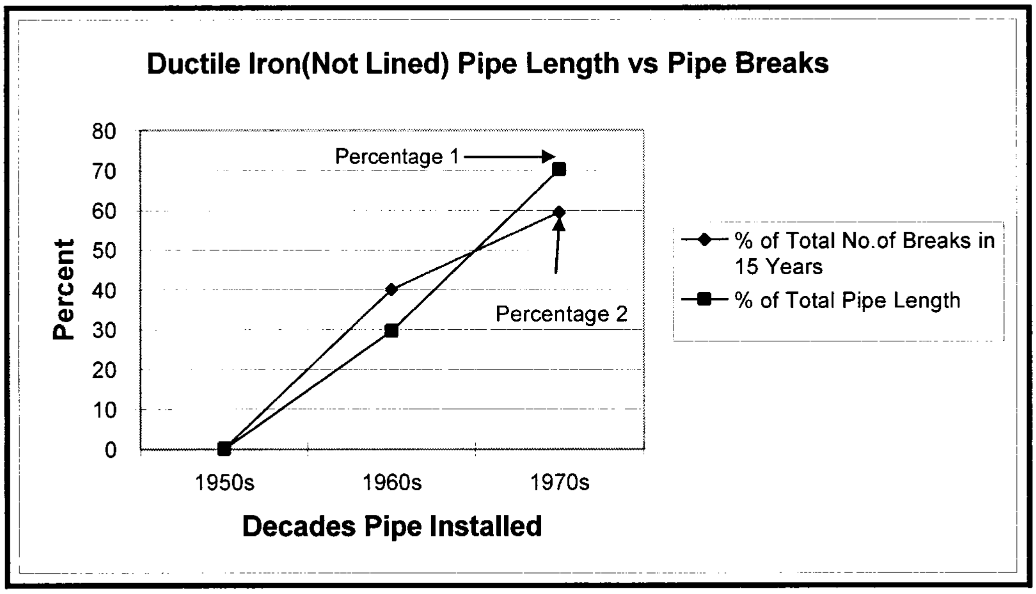

Figure 4-22 DI-NL Pipe Lengths versus Pipe Breaks by Decade of Installation

Figure 4-22 shows the two percentages of the Ductile Iron (Not Lined) pipes in Table 4-16 for comparison by year of installation. It shows that the longer the length of a group of pipes by diameter, the more breaks occurred on this group of pipes compared to others.

Table 4-17 shows the distributions of numbers of breaks and pipe lengths by decade of installation for the Ductile Iron (Lined) pipes in Quebec. For example, in 15 years between 1987 and 2001, 103 breaks that occurred on the Ductile Iron (Lined) pipes installed in the 1970s are 35.64% of the total 289 breaks, while the 25,083 meters of the Ductile Iron (Lined) pipes installed in the 1970s are 35.89% of the total length, 69,887 meters.

Table 4-17 Distributions of Breaks and Lengths for DI-L Pipes by Decade of Installation

Decade Pipe Installed	1970s	1980s	1990s	2000s	Total
Total No. of Breaks	103	182	4	0	289
Total Length (m)	25,083	43,429	996	378	69,887
% of Total No. of Breaks (Percentage 1)	35.64	62.98	1.38	0.00	100
% of Total Length (Percentage 2)	35.89	62.14	1.43	0.54	100

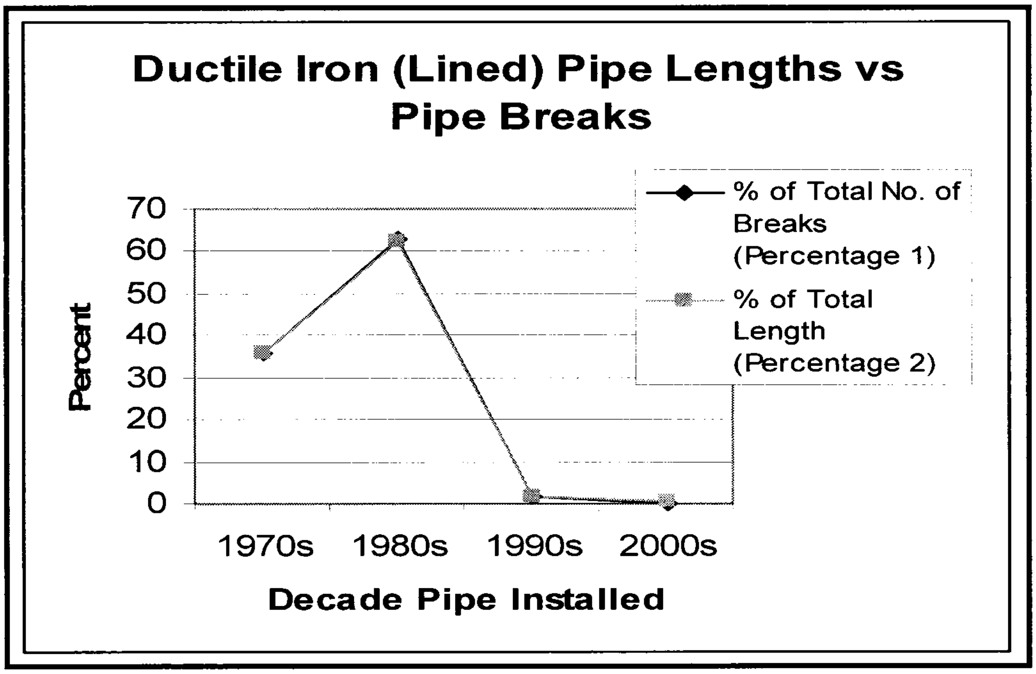

Figure 4-23 DI (Lined) Pipe Lengths versus Pipe Breaks by Decade of Installation

Figure 4-23 shows the two percentages of the Ductile Iron (Lined) pipes in Table 4-17 for comparison by year of installation. It shows that the longer the length of a group of pipes by diameter, the more breaks occurred on this group of pipes compared to others.

Table 4-18 shows the distributions of numbers of breaks and pipe lengths by decade of installation for the PVC pipes in Quebec. For example, in 15 years between 1987 and 2001, 123 breaks that occurred on the PVC pipes installed in the 1990s are 76.40% of the total 161 breaks, while the 53,966 meters of the PVC pipes installed in the 1990s is 73.83% of the total length, 73,098 meters.

Table 4-18 Distributions of Breaks and Lengths for PVC Pipes by Decade of Installation

Decade Pipe Installed	1950s	1960s	1970s	1980s	1990s	2000s	Total
Total No. of Breaks	1	0	0	34	123	3	161
Total Length (m)	59	4	430	12,598	53,966	6,041	73,098
% of Total No. of Breaks (Percentage 1)	0.62	0.00	0.00	21.12	76.40	1.86	100
% of Total Length (Percentage 2)	0.08	0.01	0.59	17.23	73.83	8.26	100

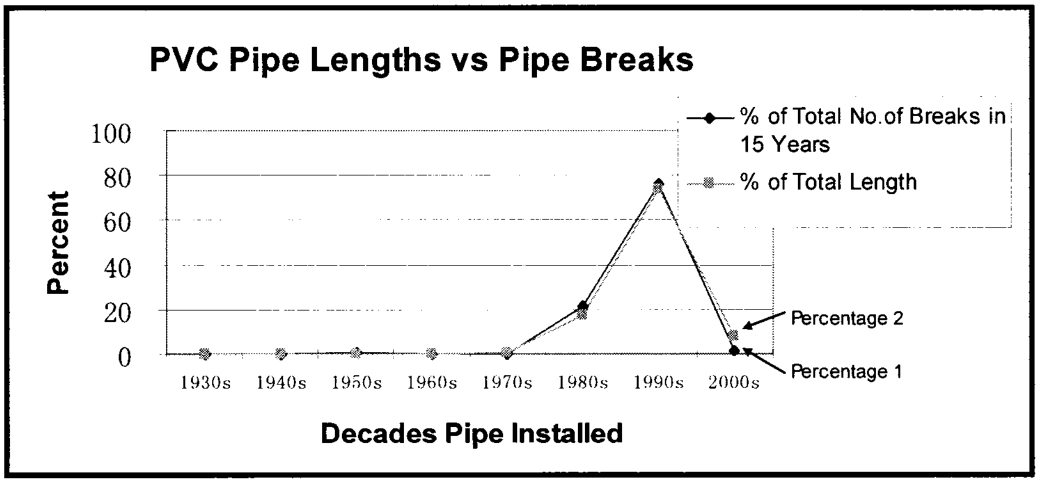

Figure 4-24 PVC Pipe Lengths versus Pipe Breaks by Decade of Installation

Figure 4-24 shows the two percentages of the PVC pipes in Table 4-18 for comparison by year of installation. It shows that the longer the length of a group of pipes by diameter, the more breaks occurred on this group of pipes compared to others.

In summary, when the two percentages as defined in Equations 4-1 and 4-2, which show the distributions of pipe breaks and pipe lengths by diameter, year and decade of installation against the total breaks and length by network or material, are compared, groups of pipes of longer pipe lengths tend to have more breaks as a global trend. However, the two percentages are not proportional to each other. There are some variances for the Ductile Iron Not Lined and Lined pipes by year of installation, which may have been caused by various environmental factors, such as different soils.

CHAPTER 5

DETERIORATION MODELS

5.1 General

The existing models found in the literature have been applied to available water main data sets. The results are thoroughly discussed. New models are developed according to the modeling procedures listed in Chapter 3 in order to find out factors that jointly contribute to the annual break rates of individual water mains in a water main network. The new models can be used for economic analysis of individual water mains, which can be incorporated into the development of an asset management system for municipal infrastructure systems. The developed models are tested for statistical significance. Validation and sensitivity analysis are conducted. Limitations of the developed models are summarized. A preliminary condition rating scale is proposed.

5.2 Application of Existing Models to Available Data Sets

Clark et al. (1982) models require data on the percent of pipe laid in residential areas or industrial areas, the pipe lengths or the surface areas in corrosive soil, the age of pipe from the first break, the pipe differential pressure and absolute pressure. McMullen (1982) Model requires data about the saturated resistivity, PH and redox potentials of soils. Jacobs and Karney (1994) Model needs detailed information such as the exact location and the dates of breaks in order to determine whether a pipe break is independent. Hatfield (1987) model uses the accumulated number of breaks as the dependent variable and concludes that the prediction for specific water mains can not be generated from water main data in large quantities. Probabilistic models also need detailed information on operation and soil conditions. With only limited water main data collected, such models can not be used. The exponential models of Shamir and Howard (1979) and Walski and Pelliccia (1982) have been discussed below and applied to the Quebec data. According to Shamir and Howard (1979), the exponential model may be applied to individual pipes, a group of homogenous pipes or even a whole pipe network. However, there are no details about how their model being applied to individual pipes. It is generally agreed that this model needs to be applied to water mains in homogenous groups (Kleiner and Rajani, 2001a).

Without data about soil and traffic loading, the Quebec water mains are grouped according to the time of installation and the diameter. The data contain the pipes of the same diameter installed within a decade, or the pipes of all diameters installed within a decade etc..

Tables 5-1 shows the break rates (number of breaks/km) for the years between 1987 and 2001 of the groups formed for the Grey Cast Iron pipes. For example, the 150 mm Grey Cast Iron pipes installed in the 1950s have a length of 35.42 Km, and break rates: 0.45, 0.51, 0.56, 0.45, 0.73, 0.56, 0.79, 0.42, 0.42, 0.48, 0.4, 0.4, 0.45, 0.15 for the year from 1987 to 2001 respectively.

Tables 5-2 and 5-3 show the break rates (number of breaks/km) for the years between 1987 and 2001 of the groups formed for the Ductile Iron Not Lined and Lined pipes.

Assumptions are made that some of these groups may have shared a similar deterioration process over years in the past.

Figures 5-1 and 5-2 show the plots of the models of Shamir and Howard (1979), and of Walski and Pelliccia (1982). The figures are based on the base year to be 1987, the end year 2001. For the Walski and Pelliccia (1982) Model, both pipe (pit cast iron, and sandspun cast iron) groups are assumed to be installed in 1950. The break rates, the number of breaks/ 1000 ft and the number of breaks/ mile are plotted respectively against the years between 1987 and 2001 for these two models by selecting parameters that are suggested in the literature.

Walski and Pelliccia (1982) have reported that the regression parameters they obtained are in accordance with those of Shamir and Howard (1979). Walski and Pelliccia (1982) have used pipe age(t-k) rather than $(t\text{-}t_0)$ in their analysis.

However, these two models are actually the same considering the exponential growth of the break rate (number of breaks/length) against time. Shamir and Howard (1979) Model has been applied to the Quebec data to see how good the model might fit the actual data. Better results (deviations of forecasted break rates compared to actual values) exist to several groups with larger total lengths, such as the 150 mm Grey Cast Iron pipes installed in the 1950s, and the 150 mm Ductile Iron (Lined and Not Lined) pipes installed in the 1970s, with certain sets of chosen parameters. Other groups have major deviations. The results are not consistent. For all the groups established, the actual break rates (number of breaks/length) do not always increase between 1987 and 2001. The yearly break rates are very diverse, as can be seen in Tables 5-1, 5-2, and 5-3, which show the break rates of these groups from 1987 to 2001 for the Grey Cast Iron, Ductile Iron (Not Lined and Lined) pipes. The results that come from applying the model to the data groups from Quebec are not consistent, probably because no real homogenous groups are formed due to the lack of certain data such as soil information, cathodic protection for metallic pipes, and other operation and maintenance records. On the other hand, both models of Shamir and Howard (1979) and Walski and Pelliccia (1982) focus on break rate (number of breaks/length) against a time (pipe ages or $t-t_0$), which may be inadequate. Maintenance or previous replacement of failed pipes may have significant impact in the future deterioration of water mains, thus time alone might not be a good indictor in predicting pipe break rates even though homogenous pipe groups can be formed.

Figure 5-3 shows the break rates plots of the 150 mm Grey Cast Iron pipes installed in the 1950s compared to three forecasted break rates based on the Shamir and Howard (1979) Model by using model parameters as suggested in the literature.

Figures 5-4 and 5-5 show similar plots of the break rates of the 150 mm Ductile Iron Not Lined and Lined pipes installed in the 1950s compared to three forecasted break rates based on the Shamir and Howard (1979) Model by using suggested model parameters from the literature.

Table 5-1 Grey Cast Iron Pipe Break Rate (no. of breaks/km) by Diameter and Decade of Installation

Pipe Characteristics			Break Rate- No. of Breaks/ Km														
Pipe Diameter (mm)	Decades Pipe Installed	Length (Km)	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
All	All	129.85	0.35	0.45	0.48	0.38	0.45	0.45	0.52	0.48	0.37	0.3	0.41	0.42	0.31	0.31	0.13
100	1950s	1.1	1.82	0.91	0.91	0.91	0	0	0	0	0	0	0.91	0	0.91	0	0.91
100	1960s	1.17	0.86	1.71	1.71	0.86	1.71	1.71	0	1.71	0	0	1.71	0	0	0	0.86
150	1950s	35.42	0.45	0.51	0.56	0.45	0.73	0.56	0.79	0.42	0.42	0.48	0.4	0.4	0.45	0.45	0.14
150	1960s	37.01	0.41	0.59	0.51	0.43	0.62	0.54	0.73	0.7	0.49	0.3	0.46	0.84	0.43	0.27	0.22
200	1950s	11.63	0.17	0.52	0.43	0.34	0.34	0.34	0.34	0.43	0.43	0.34	0.6	0.17	0.26	0.43	0.09
200	1960s	11.17	0.36	0.36	0.27	0.36	0	0.54	0.27	0.45	0.09	0.36	0.36	0.36	0	0.09	0.09
250	1950s	4.86	0.21	0.62	1.03	0.21	0.21	0	0.21	0.21	0	0.21	0.21	0	0.21	0.62	0
300	1960s	3.46	0.29	0	0	0	0	0.29	0	0.29	0.29	0	0.58	0	0	0.29	0
300	1950s	2.59	0.39	0	0.77	0.77	0	0	0.77	0.77	0	0	0	0.39	0.39	0	0
350&400	1950s&1960s	5.44	0.18	0	0	0.18	0	0.18	0	0	0	0	0.18	0	0	0	0
500+	1940s-1970s	4.31	0	0	0.23	0	0	0	0.23	0	0	0.23	0.46	0	0	0	0

Table 5-2 Ductile Iron (Not Lined) Pipe Break Rate (no of breaks/km) by Diameter and Decade of Installation

Pipe Characteristics			Break Rate- No. of Breaks/ Km														
Pipe Diameter (mm)	Decades Pipe Installed	Length (Km)	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
All	All	66.98	0.48	0.39	0.33	0.42	0.25	0.36	0.33	0.45	0.19	0.33	0.4	0.25	0.21	0.27	0.03
150	60s	9.89	0.81	0.91	0.91	0.71	0.61	1.01	0.51	0.61	0.2	0.51	0.81	0.3	0.3	0.61	0.2
150	70s	23.45	0.38	0.51	0.43	0.43	0.3	0.3	0.43	0.64	0.34	0.55	0.38	0.34	0.26	0.34	0
200	60s	4.62	0.87	0.22	0.65	0.22	0.43	0.65	0.65	0.43	0	0.65	0.43	0.43	0.22	0.22	0
200	70s	9.59	0.52	0.21	0	0.42	0	0.1	0.21	0.63	0.1	0.1	0.83	0.31	0.31	0	0
300	60s	1.75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
300	70s	4.12	0.49	0	0	0.24	0.24	0.24	0.24	0	0	0	0	0	0.24	0.24	0
350+	All	7.89	0	0.13	0	0.25	0	0	0	0	0	0	0	0	0	0	0

Table 5-3 Ductile Iron (Lined) Pipe Break Rate (no of breaks/km) by Diameter and Decade of Installation

Pipe Characteristics			Break Rate- Number of Breaks/ Km														
Pipe Diameter (mm)	Decades Pipe Installed	Length (Km)	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
All	All	69.89	0.24	0.31	0.37	0.24	0.27	0.33	0.34	0.39	0.24	0.23	0.3	0.24	0.36	0.17	0.09
All	70s	25.08	0.24	0.4	0.36	0.16	0.32	0.36	0.52	0.4	0.08	0.24	0.28	0.12	0.44	0.2	0
All	80s	44.8	0.25	0.27	0.38	0.29	0.25	0.31	0.25	0.38	0.33	0.22	0.31	0.31	0.31	0.16	0.13
150	70s	13.02	0.38	0.77	0.61	0.23	0.61	0.38	0.38	0.61	0.15	0.38	0.31	0.15	0.54	0.23	0
150	80s	24.86	0.28	0.28	0.36	0.4	0.12	0.4	0.4	0.64	0.52	0.28	0.36	0.28	0.44	0.2	0.16
200	70s	5.41	0.18	0	0.18	0	0	0.55	0.55	0.18	0	0.18	0.55	0.18	0.55	0	0
250	70s	1.99	0	0	0	0.5	0	0.5	0	0	0	0	0	0	0.5	0.5	0
250	80s	4.33	0.23	0	0	0	0.46	0	0	0	0.23	0	0.69	0	0.23	0	0
300	70s	1.11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
300	80s	1.51	0	0	0.66	0	0.66	0	0	0	0	0.66	0.66	0.66	0	0	0
350+	All	7.17	0	0	0.14	0	0.14	0	0	0	0	0	0	0	0	0	0

Shamir and Howard (1979) Model- $N(t)=N(t_0)e^{A(t-t0)}$

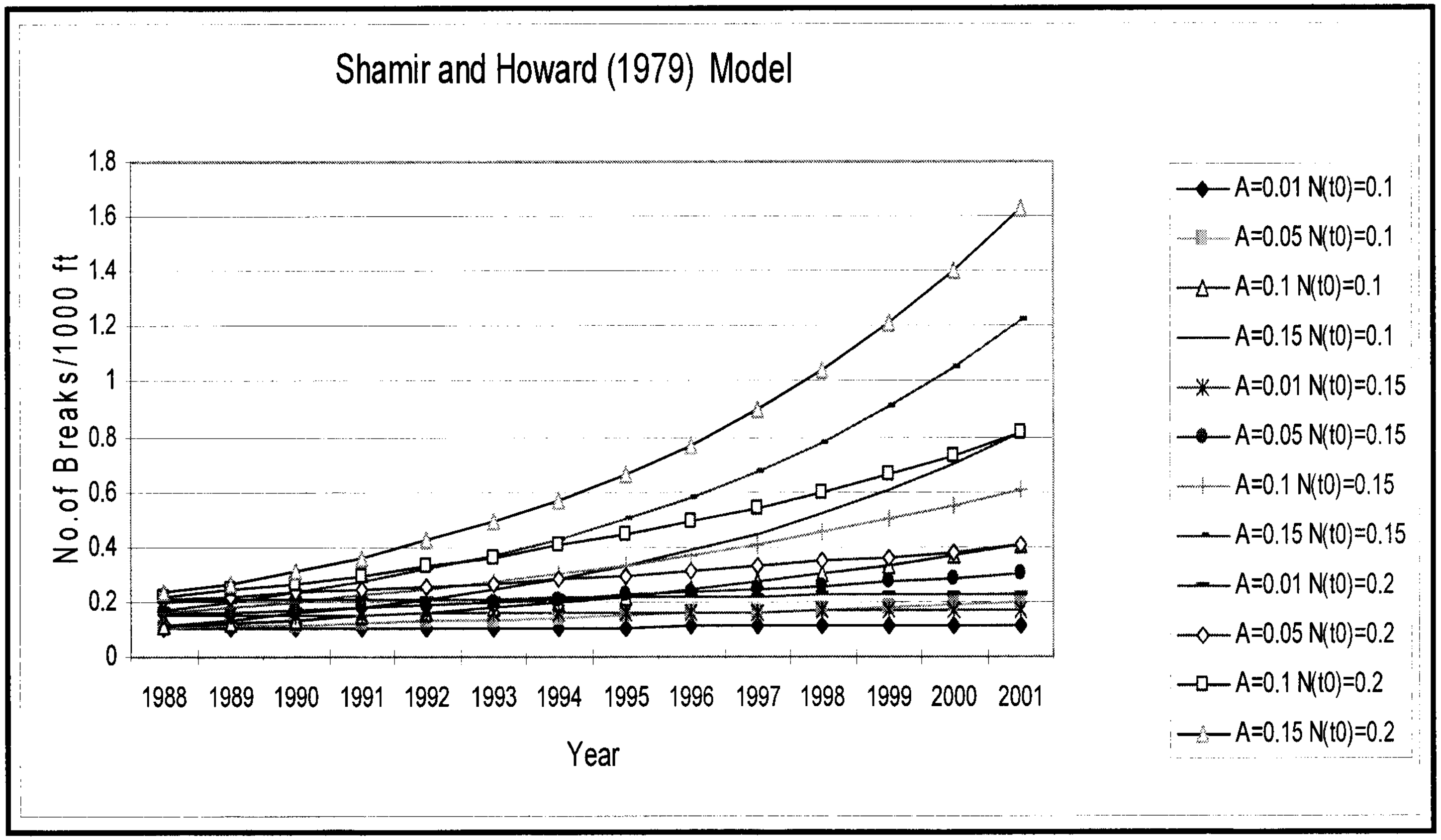

Figure 5-1 Shamir and Howard (1979) Model Break Rate by Year

Walski and Pelliccia (1982) Model- $N(t)=ae^{b(t-k)}$

K=1950, and typical values of a, b are selected from the literature for the graphical presentation of the model.

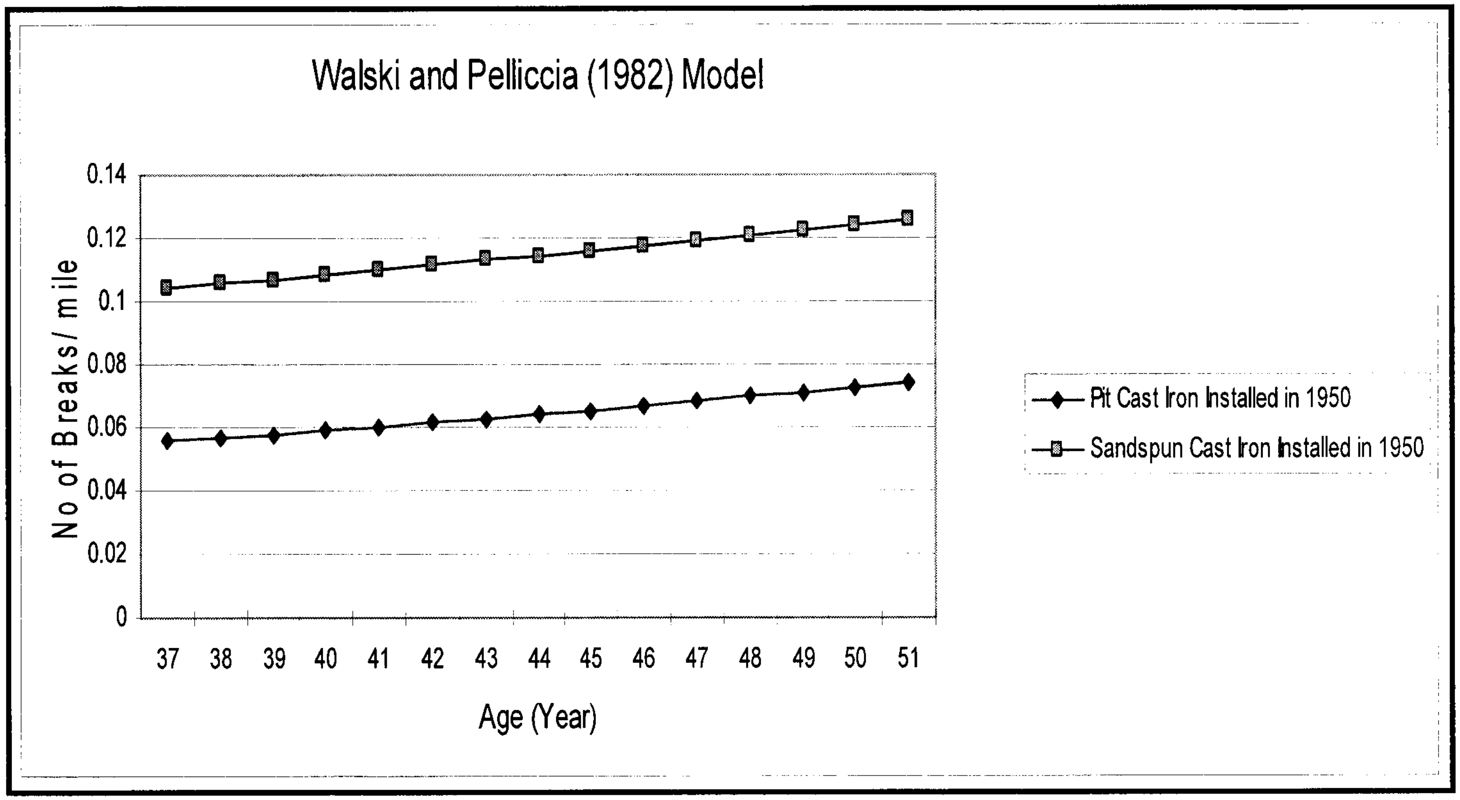

Figure 5-2 Walski and Pelliccia (1982) Model- Break Rate by Pipe Age

The three sets of actual break rates as shown in Figures 5-3, 5-4, and 5-5 all have either increasing or decreasing break rates from one year to another year. Probably maintenance events or cathodic protections installed after pipe break repairs have changed the break pattern of the group of pipes.

Tables 5-4, 5-5, and 5-6 show partial deviation results (percent of the forecasted break rates deviated from the actual break rates) for selected pipe groups of the Grey Cast Iron, Ductile Iron Not Lined and Lined pipes respectively in Quebec. Table 5-4 shows the break rate deviations of the 35.42 km, 150 mm Grey Cast Iron pipes installed in the 1950s. Table 5-5 shows the break rate deviations of the 23.45 km, 150 mm Ductile Iron (Not Lined) pipes installed in the 1950s. Table 5-6 shows the break rate deviations of the 13.2 km, 150 mm Ductile Iron (Lined) pipes installed in the 1950s.

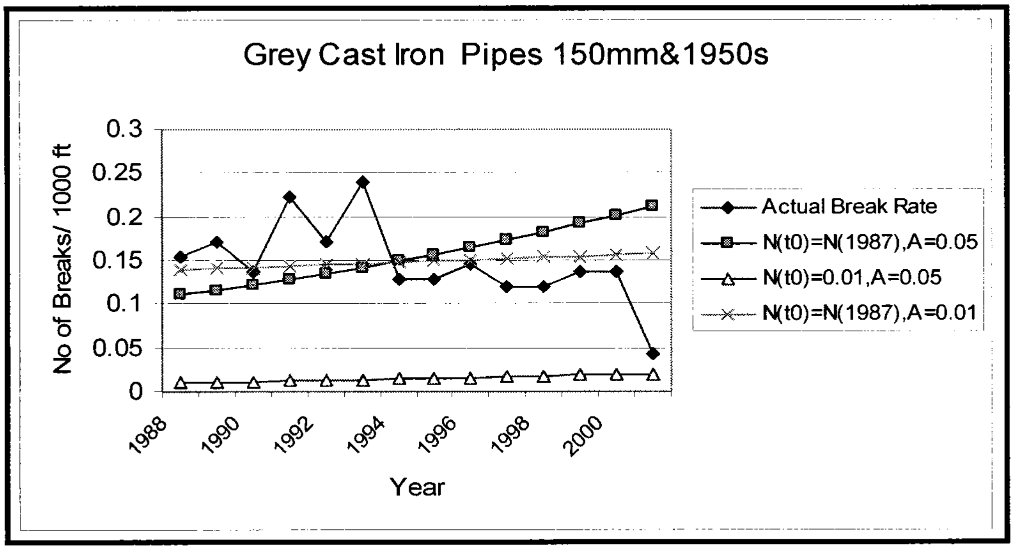

Figure 5-3 Grey Cast Iron Pipe Actual versus Forecasted Break Rates

(Diameter=150mm, Decade of Installation=1950s)

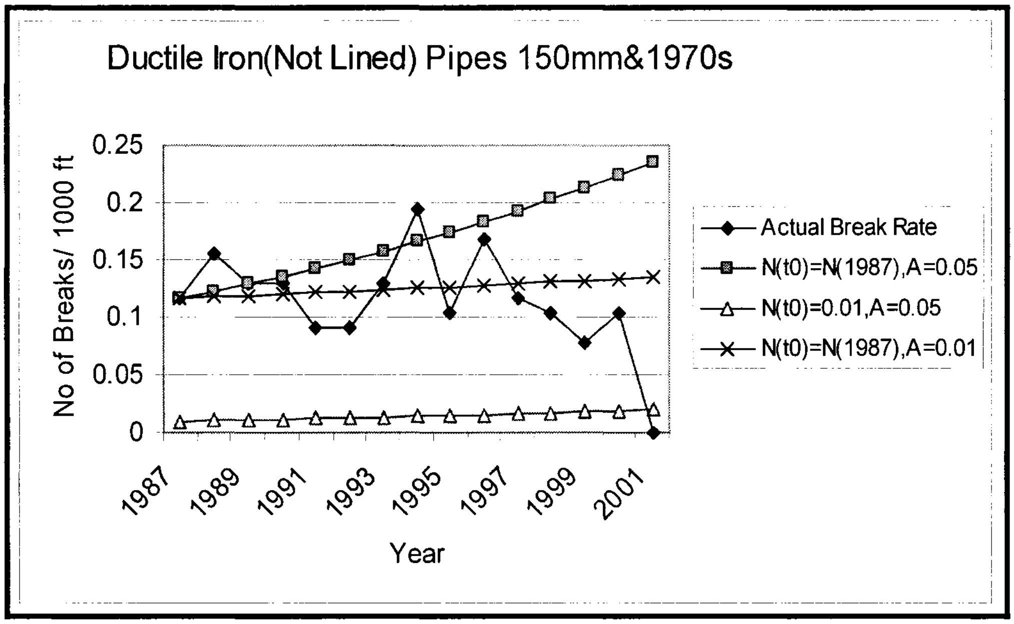

Figure 5-4 Ductile Iron (Not Lined) Pipe Actual versus Forecasted Break Rates

(Diameter=150mm, Decade of Installation=1970s)

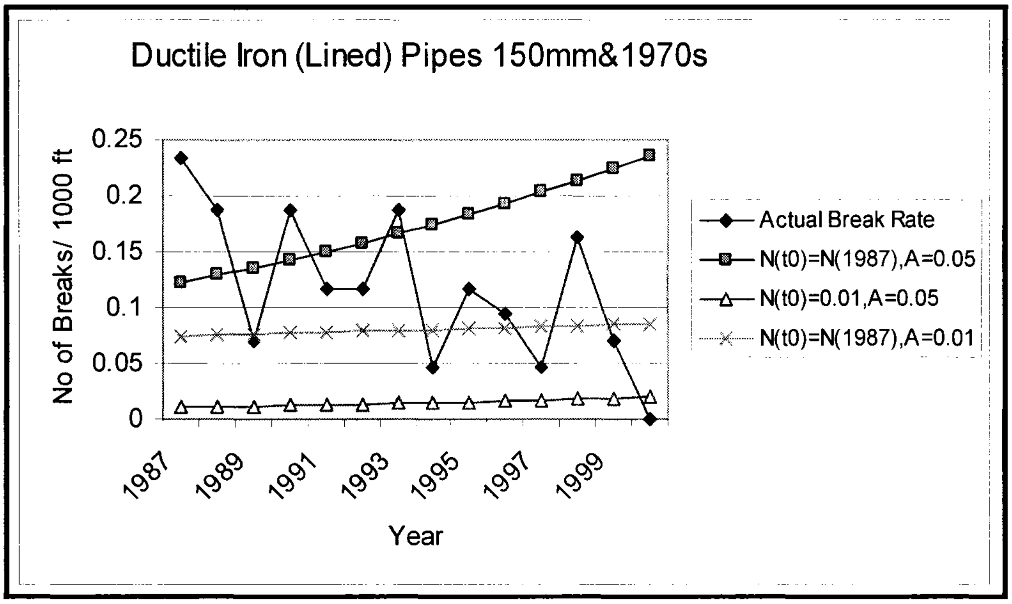

Figure 5-5 Ductile Iron (Lined) Pipe Actual versus Forecasted Break Rates

(Diameter=150mm, Decade of Installation=1970s)

Table 5-4 Grey Cast Iron Pipe Break Rate Deviations (%)
(35.42Km, Diameter=150mm, Decade of Installation=1950s)

N(t0)=N(1987), A=0.05	0	-7	-12	16	-25	3	-23	51	59	48	88	98	82	92	544
N(t0)=0.01,A=0.05	-93	-93	-94	-92	-95	-93	-94	-89	-88	-89	-86	-86	-87	-86	-53
N(t0)=N(1987), A=0.01	0	-10	-18	3	-36	-16	-39	14	16	3	26	28	13	14	268
N(t0)=N(1987), A=0.15	0	3	8	57	12	69	41	205	254	263	412	495	505	603	2513

Table 5-5 Quebec Ductile Iron (Not Lined) Pipe Break Rate Deviations (%)
(23.45KM, Diameter=150mm, Decade of Installation=1970s)

	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
N(t0)=N(1987), A=0.05	0	-21	-1	5	57	65	21	-15	68	9	65	95	173	115	-
N(t0)=0.01,A=0.05	-91	-93	-91	-91	-87	-86	-90	-93	-86	-91	-86	-83	-77	-82	-
N(t0)=N(1987), A=0.01	0	-24	-8	-7	34	35	-4	-36	22	-24	11	26	69	28	-

Table 5-6 Quebec Ductile Iron(Lined) Pipe Break Rate Deviations (%)
(13.2Km, Diameter=150mm, Decade of Installation=1970s)

	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
N(t0)=N(1987), A=0.05	0	-47	-31	94	-24	28	35	-11	273	57	106	333	30	219	-
N(t0)=0.01,A=0.05	-91	-96	-94	-83	-93	-89	-88	-92	-68	-87	-82	-63	-89	-73	-
N(t0)=N(1987), A=0.01	0	-42	-16	161	14	112	146	79	730	286	460	1202	332	1071	-

5.3 Development of New Deterioration Models

Shamir and Howard (1979) or Walski and Pelliccia(1982) Models focus on homogenous groups to analyze pipe deterioration process of these pipes as a whole. There are no complete data sets available to apply other probabilistic (proportional hazards, accelerated life, lifetime survival, and semi-Markov chain) models to individual water mains. Thus, the analysis for determining number of years until first breaks, or inter-break times of water mains is not possible.

While the models of Shamir and Howard (1979), and Walski Pelliccia (1982) are most cited and in some cases used for economical analysis of water main groups. In the present research, a new approach is planned to model the annual break rates of individual pipes, which are commonly regarded as one of the important parameters by municipalities in performance reports. The goal of this new approach is to find out what factors may jointly contribute to the deterioration process in the form of annual break rate (number of breaks/km/year). Factors are considered to include available individual pipe data: pipe age, diameter, pipe length, pipe depth and material type.

Material type is the only criterion used to group individual pipes as sets of data for further statistical analysis. In the present research work, it is assumed that the deterioration processes vary among different types of pipe materials. Seven sets of data, from both Quebec and Moncton, are organized and used for regression analysis, namely, the Grey Cast Iron, Ductile Iron (Not Lined), Ductile Iron (Lined), PVC, Hyprescon (Concrete) pipes of Quebec, and Cast Iron, Ductile Iron pipes of Moncton.

In Quebec, depths of water mains are found to be less correlated to the annual break rates. In other words, depths seem not to enhance the new models. Hence, pipe depth is excluded from further regression analysis.

The modeling process follows the procedures that are listed in Chapter 3. The first attempts have been made to develop new models by using all the data of Quebec and then apply the best selected models to the data sets of Moncton for validation purposes. Unfortunately, the results were not satisfactory and had major deviations. As mentioned earlier, the Moncton data used here are only partial of its whole water main network. This could be the reason that the developed models from the Quebec data failed to satisfy the data of Moncton.

Also attempts have been made to develop separate models using only Moncton's partial data. These models generally have resulted in R square values from 20% to 30%, compared with those of Quebec which are more than 60%. In the present research work, the Moncton data have been put aside for future use when more data can be obtained. So, the analysis focuses on the Quebec data. In order to leave some data for model validation purposes, 20% of data for each pipe group are selected randomly using Microsoft Excel Software. The rest of 80% data are used for model building. In general, LogR ($Log_{10}R$) is set as the dependent variable and studied against the independent variables of L,A,S,L2,A2,S2,L×A,L×S,A×S,LogL,LogA, and LogS, which are length (m), age at 2001 (years), size (mm),square of length (m^2), square of pipe age at 2001($year^2$), square of pipe size (mm^2), length times age at 2001, length times size, age at 2001 times size, $Log_{10}S$, $Log_{10}L$, and $log_{10}A$ respectively. R is the normalized annual break rate (number of breaks/km/year) obtained from 15 years (1987-2001) of break data.

5.3.1 Modeling for Grey Cast Iron Pipes

The best subset regressions were carried out by using Minitab software. One of the best subset regression results are shown in Figure 5-6. LogR versus LogL, LogA, LogS, A×S are chosen for multiple regression since the subset has a relatively high R Square of 68.4% compared to the highest R Square of 69.3%, and the number of variables (4) is close to the Mallows C-P value 4.1, which indicates that a good subset may exist. Multiple regression is done accordingly and the result is shown in Figure 5-7. LogA has a p statistics equal to 0.202, which is more than the level of significance, α, as 0.1 chosen in the present study. Thus, LogA is removed and another multiple regression is implemented and the result is shown in Figure 5-8. This model resulting from the second regression is statistically significant according to p- statistics (all<0.1), but it should be noted that age related variables are excluded from the model, and an attempt is tried to include A, and A^2 into the third multiple regression to see if they may be statistically significant, too.

Figure 5-9 shows the regression results of the final model for Quebec Grey Cast Iron Pipes.

Grey Cast Iron Pipe Model Prior to Testing of Significance

The developed model for the Grey Cast Iron Pipes from the third multiple regression in Figure 5-9 is show in the following:

$$Log_{10}\mathbf{R} = 4.85-0.0206\,\mathbf{A}+0.000245\,\mathbf{A}^2+0.00281\mathbf{S}-0.905Log_{10}\mathbf{L} -1.40\,Log_{10}\mathbf{S} \quad \textbf{5-1}$$

R-Sq = 68.9% R-Sq(adj) = 68.5%

Where R= annual break rate (number of breaks/km/year)

A= water main age at 2001 (years)

S= water main size (mm)

L= water main length in GIS database (m)

Best Subsets Regression: LogR versus L, A, L2,A2,S2,L*A,L*S,A*S, LogL,LogA,LogS

Response is LogR

Vars	R-Sq	R-Sq(adj)	Mallows C-p	S	L	A	S	L2	A2	S2	L*A	L*S	A*S	LogL	LogA	LogS
1	67.9	67.8	7.9	0.20550										X		
1	47.1	47.0	257.7	0.26389	X											
2	68.1	67.9	8.1	0.20529										X	X	
2	68.0	67.9	8.5	0.20541						X				X		
3	68.6	68.4	3.7	0.20384			X							X		X
3	68.6	68.3	3.9	0.20388						X				X		X
4	69.1	68.8	-0.4	0.20246									X	X	X	X
4	68.7	68.4	4.1	0.20367			X							X	X	X
5	69.1	68.7	1.4	0.20268					X				X	X	X	X
5	69.1	68.7	1.5	0.20270		X							X	X	X	X
6	69.2	68.7	2.8	0.20276		X			X				X	X	X	X
6	69.2	68.7	3.1	0.20285	X							X	X	X	X	X
7	69.2	68.6	4.4	0.20294					X		X	X	X	X	X	X
7	69.2	68.6	4.6	0.20298						X	X	X	X	X	X	X
8	69.3	68.6	5.7	0.20302		X			X		X	X	X	X	X	X
8	69.3	68.6	5.9	0.20307	X	X			X			X	X	X	X	X
9	69.3	68.6	7.4	0.20320		X		X	X		X	X	X	X	X	X
9	69.3	68.6	7.4	0.20321	X	X		X	X			X	X	X	X	X
10	69.3	68.5	9.2	0.20344	X	X		X	X	X		X	X	X	X	X
10	69.3	68.5	9.3	0.20345	X	X		X	X		X	X	X	X	X	X
11	69.3	68.4	11.1	0.20367	X	X	X	X	X	X		X	X	X	X	X
11	69.3	68.4	11.1	0.20368	X	X		X	X	X	X	X	X	X	X	X
12	69.3	68.3	13.0	0.20392	X	X	X	X	X	X	X	X	X	X	X	X

Figure 5-6 Best Subsets Regression of Grey Cast Iron Pipes

```
Regression Analysis: LogR versus S, LogL, LogA, LogS

The regression equation is
LogR = 4.57 + 0.00266 S - 0.905 LogL - 0.187 LogA - 1.31 LogS


Predictor        Coef     SE Coef       T      P
Constant       4.5673      0.9141    5.00  0.000
S           0.0026598   0.0009446    2.82  0.005
LogL         -0.90454     0.03150  -28.71  0.000
LogA          -0.1867      0.1461   -1.28  0.202
LogS          -1.3141      0.4678   -2.81  0.005


S = 0.203674   R-Sq = 68.7%   R-Sq(adj) = 68.4%


Analysis of Variance

Source           DF       SS      MS       F      P
Regression        4  34.2984  8.5746  206.70  0.000
Residual Error  376  15.5976  0.0415
Total           380  49.8961


Source   DF   Seq SS
S         1   0.0004
LogL      1  33.8963
LogA      1   0.0744
LogS      1   0.3274
```

Figure 5-7 1st Multiple Regression of Grey Cast Iron Pipes

```
Regression Analysis: LogR versus S, LogL, LogS

The regression equation is
LogR = 4.28 + 0.00268 S - 0.902 LogL - 1.33 LogS


Predictor        Coef     SE Coef       T      P
Constant       4.2844      0.8877    4.83  0.000
S           0.0026828   0.0009453    2.84  0.005
LogL         -0.90223     0.03148  -28.66  0.000
LogS          -1.3270      0.4680   -2.84  0.005


S = 0.203845   R-Sq = 68.6%   R-Sq(adj) = 68.4%


Analysis of Variance

Source           DF      SS      MS       F      P
Regression        3  34.231  11.410  274.60  0.000
Residual Error  377  15.665   0.042
Total           380  49.896


Source  DF  Seq SS
S        1   0.000
LogL     1  33.896
LogS     1   0.334
```

Figure 5-8 2nd Multiple Regression for Grey Cast Iron Pipes

```
Regression Analysis: LogR versus A, A2, S, LogL, LogS

The regression equation is
LogR = 4.85 - 0.0206 A + 0.000245 A2 + 0.00281 S - 0.905 LogL - 1.40 LogS


Predictor         Coef    SE Coef       T      P
Constant        4.8498     0.9391    5.16  0.000
A             -0.02062    0.01124   -1.84  0.067
A2           0.0002450  0.0001375    1.78  0.075
S            0.0028063  0.0009488    2.96  0.003
LogL          -0.90521    0.03149  -28.75  0.000
LogS           -1.3964     0.4706   -2.97  0.003


S = 0.203471   R-Sq = 68.9%   R-Sq(adj) = 68.5%


Analysis of Variance

Source           DF       SS      MS       F      P
Regression        5  34.3709  6.8742  166.04  0.000
Residual Error  375  15.5252  0.0414
Total           380  49.8961


Source  DF   Seq SS
A        1   0.0364
A2       1   0.0098
S        1   0.0001
LogL     1  33.9600
```

Figure 5-9 3rd Multiple Regression of Grey Cast Iron Pipes

Testing for Significance of Grey Cast Iron Pipe Model

Chapter 2 presents how to carry out testing of significance of multiple regression models in details, and the details of the testing are shown below.

F Test

Based on Figure 5-9, because the Test Statistic F= 166>F_{α}= $F_{0.1}$ = 1.862693 (Obtained from Microsoft Excel), or, p-value=0.000<α=0.1, the level of significance chosen for the present study, the hypothesis H_0 (β_i=0) can be rejected, and H_a: (one or more of the parameters are not equal to zero) is true. A significant overall relationship is present for the Model in Equation 5-1.

t Test

Based on Figure 5-9, the values of Test Statistic $t_i = b_i/S_{bi}$ and p statistics are as follows:

t_1=-1.84 p_1=0.067, t_2=1.78 p_2=0.075, t_3=2.96 p_3=0.003,

t_4=-28.75 p_4=0.000, t_5=-2.97 p_5=0.003

Because t_1, t_4, t_5 <- $t_{\alpha/2}$, and t_2 ,t_3 > $t_{\alpha/2}$ $t_{\alpha/2}$ = $t_{0.05}$= 1.648927 (Obtained from Microsoft Excel), or, p_1, p_2, p_3, p_4 , p_5)<α=0.1, the hypothesis H_0 (β_i=0) can be rejected, and H_a ($\beta_i \neq 0$) is true. A significant individual relationship is present for the Model in Equation 5-1.

According to the above F test and t test results, the Grey Cast Iron Pipe Model has both an overall statistical significance and individual statistical significance. Hence, the model can go through the validation process.

Grey Cast Iron Pipe Model Validation

The Grey Cast Iron Pipe Model was validated according to the validation procedures defined in Chapter 2. The validation was based on the 20% of data that were randomly selected. The results are as follows:

Average Invalidity Percent: $AIP = (\sum_{i=1}^{n} |1-(E_i/C_i)|)/n$= 37/95=39.2%

Average Validity Percent: AVP = 1-AIP=1-39.2%=60.8%

Table 5-7 shows partial data of the validation results of the Grey Cast Iron Pipe Model.

Table 5-7 Validation Results of the Grey Cast Iron Pipe Model (Partial)

#	Actual Annual Break Rate (Ci)	Predicted Annual Break Rate (Ei)	1- Ei/Ci	Absolute Difference | 1-Ei/Ci |
2	0.86	1.56	-0.82	0.82
3	1.83	3.11	-0.70	0.70
17	3.01	3.79	-0.26	0.26
21	2.15	2.78	-0.29	0.29
47	1.31	1.77	-0.35	0.35
58	0.99	1.38	-0.40	0.40
63	0.96	1.35	-0.40	0.40
163	0.71	1.07	-0.52	0.52
279	1.06	1.34	-0.27	0.27
281	1.00	1.29	-0.29	0.29
288	0.61	0.84	-0.37	0.37
289	0.75	1.00	-0.34	0.34
292	0.96	1.29	-0.35	0.35
295	1.20	1.53	-0.27	0.27
...	...	...	...	...
300	0.65	0.88	-0.35	0.35
305	2.33	3.04	-0.30	0.30
465	1.80	0.67	0.63	0.63
473	8.44	1.77	0.79	0.79
476	3.23	0.50	0.85	0.85
			∑ | 1- Ei/Ci |=	37
			Number of data for validation, n=	95
			Average Invalidity Percent, AIP= (∑ | 1- Ei/Ci |)/n	39.2%

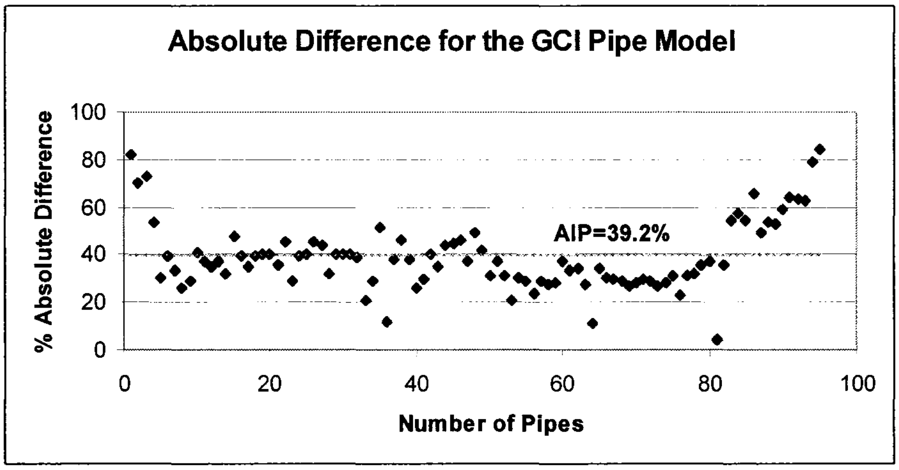

Figure 5-10 Validation Chart for the Grey Cast Iron Pipe Model

Figure 5-10 shows the absolute differences ($|1-(E_i/C_i)|$ for the Grey Cast Iron Pipe Model.

According to the AVP, this model is 60.8% validated to the 20% of data that are randomly selected. The result is moderately satisfactory. Considering the limit of the data and the complex of deterioration itself, the result is considered acceptable.

5.3.2 Modeling for Ductile Iron (Not Lined) Pipes

Best subsets regression was conducted with LogR ($Log_{10}R$) as the dependent variable and L,A,S,L2,A2,S2,L×A,L×S,A×S, LogL,LogA and LogS as the independent variables. The best subsets regression was not able to take the full dependent variables for there were some correlations existing between these sets of variables. Figure 5-11 shows the Best Subsets Regression Results with the set of independent variables L2,L2,S2 removed. The best subset with 8 variables and a Mallows C-p of 8 was selected for a multiple regression. The regression results were shown in Figure 5-12. With level of significance, α, as 0.1, the dependent variables with p values more than 0.1 were removed from further regression trials. Finally, the multiple regression was conducted between the dependent variable, LogR, and the independent variable, LogL, as shown in Figure 5-13.

```
Best Subsets Regression: LogR versus L,A,S,L*A,L*S,A*S,LogL,LogA,LogS

Response is LogR

                                                            L L L
                                                      L L A o o o
                            Mallows                   * * * g g g
Vars  R-Sq  R-Sq(adj)         C-p        S  L A S A S S L A S
   1  65.0       64.8        -0.7  0.22362              X
   1  49.0       48.6        65.3  0.26994  X
   2  65.3       64.8         0.1  0.22341      X       X
   2  65.3       64.8         0.2  0.22353            X X
   3  65.4       64.7         1.8  0.22395      X   X   X
   3  65.4       64.7         1.8  0.22395      X X     X
   4  65.6       64.6         3.0  0.22411  X     X   X X
   4  65.6       64.6         3.0  0.22412      X   X   X   X
   5  65.9       64.7         3.6  0.22375          X X X X X
   5  65.8       64.7         3.8  0.22395    X     X X X   X
   6  66.1       64.7         4.8  0.22392  X     X   X X X X
   6  66.1       64.6         5.0  0.22405  X X   X   X X   X
   7  66.3       64.6         6.2  0.22419  X     X X X X X X
   7  66.2       64.5         6.4  0.22435  X X   X X X X   X
   8  66.3       64.4         8.0  0.22487  X X   X X X X X X
   8  66.3       64.3         8.2  0.22499  X   X X X X X X X
   9  66.3       64.1        10.0  0.22567  X X X X X X X X X
```

Figure 5-11 Best Subsets Regression of Ductile Iron (Not Lined) Pipes

```
Regression Analysis: LogR versus L, S, L*A, L*S, A*S, LogL, LogA, LogS

The regression equation is
LogR = - 4.85 - 0.00440 L + 0.00031 S + 0.000145 L*A + 0.000004 L*S
       - 0.000214 A*S - 0.974 LogL + 1.91 LogA + 2.24 LogS

Predictor         Coef     SE Coef      T      P
Constant        -4.847       4.327  -1.12  0.265
L            -0.004399    0.003684  -1.19  0.234
S             0.000307    0.004728   0.06  0.948
L*A          0.0001450   0.0001346   1.08  0.283
L*S         0.00000403  0.00000516   0.78  0.436
A*S         -0.0002144   0.0001491  -1.44  0.153
LogL           -0.9739      0.1453  -6.70  0.000
LogA             1.906       1.795   1.06  0.290
LogS             2.238       1.580   1.42  0.159

S = 0.224989   R-Sq = 66.3%   R-Sq(adj) = 64.3%

Analysis of Variance

Source           DF       SS      MS      F      P
Regression        8  13.9119  1.7390  34.35  0.000
Residual Error  140   7.0868  0.0506
Total           148  20.9987

Source  DF   Seq SS
L        1  10.2873
S        1   0.1841
L*A      1   0.0120
L*S      1   1.1040
A*S      1   0.0029
LogL     1   2.1923
LogA     1   0.0277
LogS     1   0.1015
```

Figure 5-12 1st Multiple Regression for Ductile Iron (Not Lined) Pipes

```
Regression Analysis: LogR versus LogL

The regression equation is
LogR = 1.83 - 0.911 LogL

Predictor      Coef   SE Coef       T      P
Constant    1.82638   0.09659   18.91  0.000
LogL       -0.91089   0.05514  -16.52  0.000

S = 0.223625   R-Sq = 65.0%   R-Sq(adj) = 64.8%

Analysis of Variance

Source           DF      SS      MS       F      P
Regression        1  13.648  13.648  272.91  0.000
Residual Error  147   7.351   0.050
Total           148  20.999
```

Figure 5-13 Final Multiple Regression for Ductile Iron (Not Lined) Pipes

Ductile Iron(Not Lined)Pipe Model Prior to Testing of Significance

The developed model for the Ductile Iron (not lined) Pipes in Figure 5-13 has the following form:

$Log_{10}\mathbf{R} = 1.83 - 0.911\ Log_{10}\mathbf{L}$..**5-2**

R-Sq = 65.0% R-Sq(adj) = 64.8%

Testing for Significance of Ductile Iron(Not Lined)Pipe Model

Same testing of significance procedures was done to this model, and the details of the testing are shown below.

F Test

Based on Figure 5-13, because the Test Statistic F= 272.91>F_{α}= $F_{0.1}$ = 1.862693 (Obtained from Microsoft Excel), or, p-value=0.000<α=0.1, the level of significance chosen for the present study, the hypothesis H_0 (β_i=0) can be rejected,

and H_a: (one or more of the parameters are not equal to zero) is true. A significant overall relationship is present for the Model in Equation 5-2.

t Test

Based on Figure 5-13, the values of Test Statistic $t_i = b_i/S_{bi}$ and p statistics are t_1=-16.52, p_1=0.000. Because $t_{1,} <- t_{\alpha/2} = t_{0.05}$= 1.655285 (Obtained from Microsoft Excel), or p-value(p_1=0.000) <α=0.1, the hypothesis H_0 (β_i=0) can be rejected, and H_a ($\beta_i \neq 0$) is true. A significant individual relationship is present for the Model in Equation 5-2.

According to the above F test and t test results, the Ductile Iron (Not Lined) Pipe Model has both an overall statistical significance and individual statistical significance. Hence, the model can go through the validation process.

Ductile Iron (Not Lined) Pipe Model Validation

Same validation procedures as those for the Grey Cast Iron Pipe Model were carried out. The validation was based on the 20% of data that were randomly selected. The results are as follows:

$$AIP = (\sum_{i=1}^{n} |1-(E_i/C_i)|\ )/n = 16/38 = 42.1\%$$

$$AVP = 1-AIP = 1-42.1\% = 57.9\%$$

Figure 5-14 shows the absolute differences ($|1-(E_i/C_i)|$ for the Ductile Iron (Not Lined) Pipe Model.

According to the AVP, this model is 57.9% validated to the 20% of data that were randomly selected. The result is moderately satisfactory. Considering the limit of the data and the complex of deterioration itself, the result is acceptable.

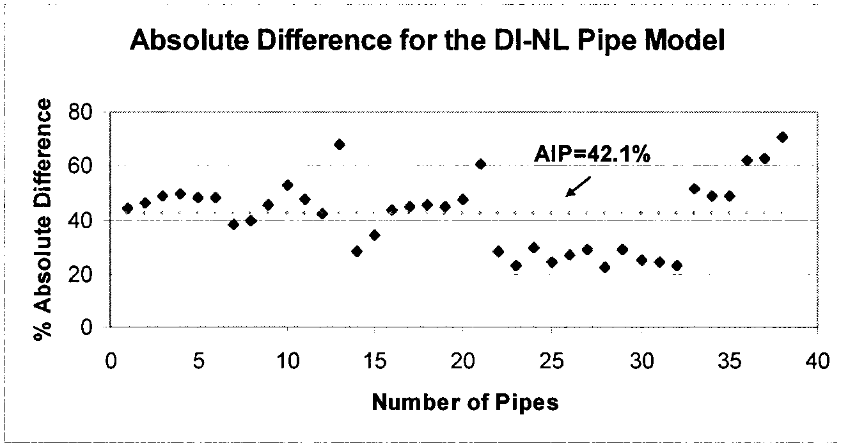

Figure 5-14 Validation Chart for the Ductile Iron (Not Lined) Pipe Model

5.3.3 Modeling for Ductile Iron (Lined) Pipes

Best subsets regression was conducted with LogR ($Log_{10}R$) as the dependent variable and L,A,S,L2,A2,S2,L×A,L×S,A×S, LogL,LogA and LogS as the independent variables. Figure 5-15 shows the Best Subsets Regression Results. The two best subsets with 11 variables and a Mallows C-p of 11 were selected for multiple regressions. One of the regression results was shown in Figure 5-16. With level of significance, α, as 0.1, the dependent variables with p values more than 0.1 were removed from further regression trials. Finally, the multiple regression was conducted between the dependent variable, LogR, and the independent variables, L×A, LogL,LogA, and LogS as shown in Figure 5-17.

```
Best Subsets Regression: LogR versus L,A,S,L2,A2,S2,L*A,L*S,A*S,LogL,LogA,LogS

Response is LogR
                                                         L L L
                                                   L L A o o o
                     Mallows                 L A S * * * g g g
Vars  R-Sq  R-Sq(adj)    C-p        S  L A S 2 2 2 A S S L A S
   1  67.7       67.5   13.3  0.20559                    X
   1  44.5       44.2  127.2  0.26956  X
   2  69.8       69.4    5.4  0.19971        X           X
   2  69.2       68.7    8.4  0.20171  X                 X
   3  70.9       70.3    1.7  0.19651        X         X X
   3  70.8       70.2    2.5  0.19707        X       X   X
   4  71.7       70.9   -0.2  0.19451              X X   X X
   4  71.6       70.8    0.3  0.19487      X       X     X X
   5  72.0       71.0    0.5  0.19425        X     X X   X X
   5  71.8       70.8    1.5  0.19495              X X   X X X
   6  72.2       71.0    1.6  0.19431  X     X     X X   X X
   6  72.1       70.9    1.8  0.19444  X   X X     X     X X
   7  72.2       70.8    3.4  0.19482  X X   X X   X X   X
   7  72.2       70.8    3.4  0.19484  X     X     X X   X X X
   8  72.3       70.7    5.1  0.19534  X X   X X   X X   X   X
   8  72.3       70.7    5.2  0.19538  X     X X   X X   X X X
   9  72.3       70.5    7.1  0.19604  X X   X X   X X   X X X
   9  72.3       70.5    7.1  0.19604  X X   X X X X X   X   X
  10  72.3       70.3    9.0  0.19669  X X X X X X X X   X   X
  10  72.3       70.3    9.1  0.19671  X   X X X X X X   X X X
  11  72.3       70.1   11.0  0.19739  X X X X X X X X X X   X
  11  72.3       70.1   11.0  0.19740  X   X X X X X X X X X X
  12  72.3       69.8   13.0  0.19810  X X X X X X X X X X X X
```

Figure 5-15 Best Subsets Regression of Ductile Iron (Lined) Pipes

```
Regression Analysis: LogR versus L,S,L2,A2,S2,L*A,L*S,A*S,LogL,LogA,LogS
The regression equation is
LogR = 3.42 - 0.00333 L + 0.00257 S + 0.000014 L2 + 0.000198 A2 - 0.000003 S2
       + 0.000159 L*A - 0.000006 L*S - 0.000023 A*S - 0.898 LogL - 0.785 LogA
       - 0.435 LogS
Predictor          Coef      SE Coef      T      P
Constant          3.421        1.429   2.39  0.018
L             -0.003330     0.003817  -0.87  0.385
S              0.002574     0.006683   0.39  0.701
L2           0.00001428   0.00000984   1.45  0.149
A2            0.0001983    0.0004028   0.49  0.623
S2          -0.00000329   0.00000878  -0.38  0.708
L*A          0.00015931   0.00009321   1.71  0.090
L*S         -0.00000627   0.00001083  -0.58  0.564
A*S          -0.0000229    0.0001098  -0.21  0.835
LogL            -0.8980       0.1659  -5.41  0.000
LogA            -0.7853       0.4991  -1.57  0.118
LogS            -0.4353       0.9521  -0.46  0.648
S = 0.197395   R-Sq = 72.3%   R-Sq(adj) = 70.1%
Analysis of Variance

Source           DF       SS      MS      F      P
Regression       11  13.9234  1.2658  32.48  0.000
Residual Error  137   5.3382  0.0390
Total           148  19.2616

Source  DF  Seq SS
L        1  8.5799
S        1  0.1051
L2       1  3.9709
A2       1  0.0002
S2       1  0.0011
L*A      1  0.0083
L*S      1  0.0049
A*S      1  0.0204
LogL     1  1.1178
LogA     1  0.1066
LogS     1  0.0081
```

Figure 5-16 1st Multiple Regression for Ductile Iron (Lined) Pipes

```
Regression Analysis: LogR versus L*A, LogL, LogA, LogS

The regression equation is
LogR = 3.36 + 0.000150 L*A - 1.11 LogL - 0.646 LogA - 0.254 LogS


Predictor          Coef       SE Coef       T      P
Constant         3.3567        0.4287    7.83  0.000
L*A          0.00014990    0.00003960    3.79  0.000
LogL           -1.11461       0.09129  -12.21  0.000
LogA            -0.6465        0.1876   -3.45  0.001
LogS            -0.2543        0.1296   -1.96  0.052


S = 0.195179    R-Sq = 71.5%    R-Sq(adj) = 70.7%


Analysis of Variance

Source           DF       SS      MS      F      P
Regression        4  13.7760  3.4440  90.41  0.000
Residual Error  144   5.4856  0.0381
Total           148  19.2616


1Source  DF   Seq SS
L*A       1   7.1187
LogL      1   6.0789
LogA      1   0.4318
LogS      1   0.1466
```

Figure 5-17 Final Multiple Regression for Ductile Iron (Lined) Pipes

Ductile Iron (Lined) Pipe Model Prior to Testing of Significance

The developed model for the Ductile Iron (Lined) pipes in Figure 5-17 has the following form:

$Log_{10}\mathbf{R} = 3.36 + 0.000150\ \mathbf{LxA} - 1.11\ Log_{10}\mathbf{L} - 0.646\ Log_{10}\mathbf{A} - 0.254\ Log_{10}\mathbf{S}$**....5-3**

R-Sq = 71.5%   R-Sq(adj) = 70.7%

Testing for Significance of Ductile Iron(Lined)Pipe Model

Same testing of significance procedures was done to this model, and the details of the testing are shown below.

F Test

Based on Figure 5-17, because the Test Statistic F= 90.41>F_α= $F_{0.1}$ = 2.00839 (Obtained from Microsoft Excel)or, p-value=0.000<α=0.1, the level of significance chosen for the present study, the hypothesis H_0 (β_i=0) can be rejected, and H_a:

(one or more of the parameters are not equal to zero) is true. A significant overall relationship is present for the Model in Equation 5-3.

t Test

Based on Figure 5-17, the values of Test Statistic $t_i = b_i/S_{bi}$ and p statistics are as follows:

t_1=3.79 p_1=0.000, t_2=-12.21 p_2=0.000, t_3=-3.45 p_3=0.001,

t_4=-1.96 p_4=0.052

Because $t_{2,}$ $t_{3,}$ t_4 <- $t_{\alpha/2,}$ and t_1 > $t_{\alpha/2}$ = $t_{0.05}$= 1.655504 (Obtained from Microsoft Excel), or, all p-values p_1, p_2, p_3, p_4 , $p_{5)}$<α=0.1, the hypothesis H_0 (β_i=0) can be rejected, and H_a ($\beta_i \neq 0$) is true. A significant individual relationship is present for the Model in Equation 5-3.

According to the above F test and t test results, the Ductile Iron (Lined) Pipe Model has both an overall statistical significance and individual statistical significance. Hence, the model can go through the validation process.

Ductile Iron (Lined) Pipe Model Validation

Same validation procedures as the above were carried out. The validation was based on the 20% of data that were randomly selected. The results are as follows:

$$AIP = (\sum_{i=1}^{n} |1-(E_i/C_i)|\ )/n = 13.2/37 = 35.7\%$$

$$AVP = 1-AIP = 1-35.7\% = 64.3\%$$

Figure 5-18 shows the absolute differences (|1-(E_i/C_i)| for the Ductile Iron (Lined) Pipe Model.

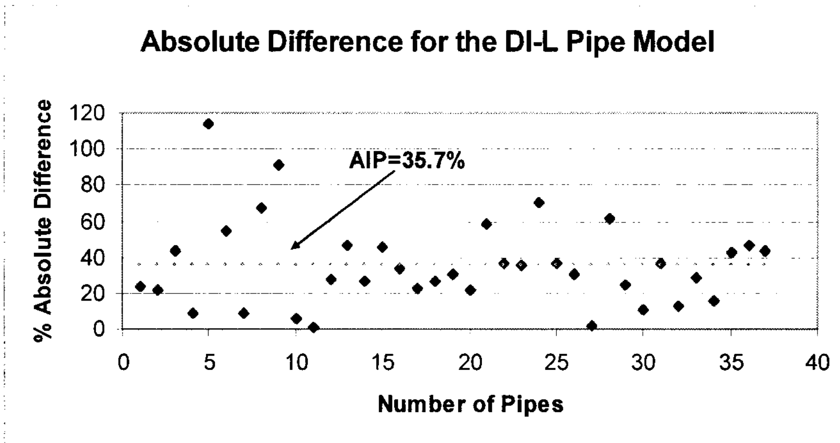

Figure 5-18 Validation Chart for the Ductile Iron (Lined) Pipe Model

According to the AVP, this model is 64.3% validated to the 20% of data that were randomly selected. The result is moderately satisfactory. Considering the limit of the data and the complex of deterioration itself, the result is acceptable.

5.3.4 Modeling for PVC Pipes

Best subsets regression was conducted with LogR ($Log_{10}R$) as the dependent variable and L,A,S,L2,A2,S2,L×A,L×S,A×S, LogL,LogA and LogS as the independent variables. Figure 5-19 shows the Best Subsets Regression Results. The two best subsets with 11 variables and a Mallows C-p of 11 were selected for multiple regressions. One of the regression results was shown in Figure 5-20. With level of significance, α, as 0.1, the dependent variables with p values more than 0.1 were removed from further regression trials. Finally, the multiple regression was conducted between the dependent variable, LogR, and the independent variables, LogL and LogA as shown in Figure 5-21.

```
Best Subsets Regression: LogR versus L,A,S,L2,A2,S2,L*A,L*S,A*S,LogL,LogA,LogS

Response is LogR

                                                         L L L
                                                   L L A o o o
                     Mallows                   L A S * * * g g g
Vars  R-Sq  R-Sq(adj)    C-p        S  L A S 2 2 2 A S S L A S
   1  66.1       65.7   51.5  0.21000                    X
   1  51.5       51.0  111.0  0.25107              X
   2  78.9       78.4    1.1  0.16653                    X X
   2  72.6       72.0   26.9  0.18980    X               X
   3  79.5       78.8    0.8  0.16515    X               X X
   3  79.5       78.7    1.0  0.16537          X         X X
   4  79.9       79.0    1.2  0.16451    X         X     X X
   4  79.8       78.9    1.4  0.16471    X   X           X X
   5  80.2       79.0    2.1  0.16439        X     X X X X
   5  80.0       78.8    2.7  0.16502    X         X X   X X
   6  80.4       79.0    2.9  0.16420    X   X   X   X   X X
   6  80.4       79.0    3.2  0.16449        X X X   X   X X
   7  80.7       79.1    3.8  0.16404    X X X   X   X   X X
   7  80.7       79.0    4.1  0.16429    X   X   X   X X X X
   8  80.8       78.9    5.6  0.16474    X X X   X   X   X X X
   8  80.8       78.9    5.6  0.16484    X X X   X   X X X X
   9  80.9       78.7    7.2  0.16540    X X X   X   X X X X X
   9  80.8       78.7    7.4  0.16563  X X X X   X   X   X X X
  10  80.9       78.5    9.0  0.16620  X X X X   X   X X X X X
  10  80.9       78.5    9.1  0.16634    X X X   X X X X X X X
  11  80.9       78.3   11.0  0.16724  X X X X X X   X X X X X
  11  80.9       78.3   11.0  0.16725  X X X X   X X X X X X X
  12  80.9       78.0   13.0  0.16831  X X X X X X X X X X X X
```

Figure 5-19 Best Subsets Regression of PVC Pipes

```
Regression Analysis: LogR versus L,A,S,L2,S2,L*A,L*S,A*S,LogL,LogA,LogS

The regression equation is
LogR = 0.89 + 0.00112 L + 0.0299 A - 0.00641 S + 0.000007 L2 + 0.000016 S2
       + 0.000003 L*A - 0.000019 L*S - 0.000132 A*S - 0.760 LogL - 0.917 LogA
       + 1.06 LogS
Predictor         Coef      SE Coef      T      P
Constant         0.890        2.226   0.40  0.690
L             0.001119     0.003089   0.36  0.718
A              0.02995      0.02793   1.07  0.287
S            -0.006413     0.006597  -0.97  0.334
L2          0.00000724   0.00000922   0.79  0.434
S2          0.00001570   0.00001108   1.42  0.160
L*A          0.0000034    0.0002052   0.02  0.987
L*S        -0.00001889   0.00000963  -1.96  0.053
A*S         -0.0001321    0.0002008  -0.66  0.512
LogL           -0.7597       0.1988  -3.82  0.000
LogA           -0.9169       0.3054  -3.00  0.004
LogS             1.060        1.322   0.80  0.425

S = 0.167246   R-Sq = 80.9%   R-Sq(adj) = 78.3%

Analysis of Variance
Source          DF        SS       MS      F      P
Regression      11   9.36808  0.85164  30.45  0.000
Residual Error  79   2.20973  0.02797
Total           90  11.57781
Source  DF   Seq SS
L        1  5.09470
A        1  0.44577
S        1  0.75536
L2       1  1.10039
S2       1  0.10825
L*A      1  0.26915
L*S      1  0.68168
A*S      1  0.34397
LogL     1  0.26732
LogA     1  0.28352
LogS     1  0.01798
```

Figure 5-20 1st Multiple Regression for PVC Pipes

```
Regression Analysis: LogR versus LogL, LogA

The regression equation is
LogR = 2.69 - 0.898 LogL - 0.745 LogA


Predictor        Coef   SE Coef       T      P
Constant       2.6872    0.1423   18.88  0.000
LogL         -0.89772   0.05160  -17.40  0.000
LogA         -0.7448     0.1018   -7.32  0.000


S = 0.166529    R-Sq = 78.9%    R-Sq(adj) = 78.4%


Analysis of Variance

Source          DF       SS      MS       F      P
Regression       2   9.1374  4.5687  164.75  0.000
Residual Error  88   2.4404  0.0277
Total           90  11.5778


Source  DF  Seq SS
LogL     1  7.6530
LogA     1  1.4844
```

Figure 5-21 Final Multiple Regression for PVC Pipes

PVC Pipe Model Prior to Testing of Significance

The developed model for the PVC Pipes in Figure 5-21 has the following form:

$Log_{10}\mathbf{R} = 2.69 - 0.898\ Log_{10}\mathbf{L} - 0.745\ Log_{10}\mathbf{A}$ **5-4**

R-Sq = 78.9%   R-Sq(adj) = 78.4%

Testing for Significance of PVC Pipe Model

Same testing of significance procedures was done to this model, and the details of the testing are shown below.

F Test

Based on Figure 5-21, because the Test Statistic $F = 164.75 > F_{\alpha} = F_{0.1} = 2.335218$ (Obtained from Microsoft Excel), or, p-value=0.000<α=0.1, the level of significance chosen for the present study, the hypothesis H_0 (β_i=0) can be rejected,

and H_a: (one or more of the parameters are not equal to zero) is true. A significant overall relationship is present for the Model in Equation 5-4.

t Test

Based on Figure 5-21, the values of Test Statistic $t_i = b_i/S_{bi}$ and p statistics are as follows:

t_1=-17.40 p_1=0.000, t_2=-7.32 p_2=0.000

Because t_1, t_2, <- $t_{\alpha/2}$=1.662354 (Obtained from Microsoft Excel), or, all p-values p_1, p_2 <α=0.1, the hypothesis H_0 (β_i=0) can be rejected, and H_a ($\beta_i \neq 0$) is true. A significant individual relationship is present for the Model in Equation 5-4.

According to the above F test and t test results, the PVC Pipe Model has both an overall statistical significance and individual statistical significance. Hence, the model can go through the validation process.

PVC Pipe Model Validation

Same validation procedures as the above were carried out. The validation was based on the 20% of data that were randomly selected. The results are as follows:

$$AIP = \left(\sum_{i=1}^{n} |1-(E_i/C_i)|\right)/n = 7.47/23 = 32.5\%$$

$$AVP = 1-AIP = 1-32.5\% = 67.5\%$$

Figure 5-22 shows the absolute differences ($|1-(E_i/C_i)|$) for the PVC Pipe Model.

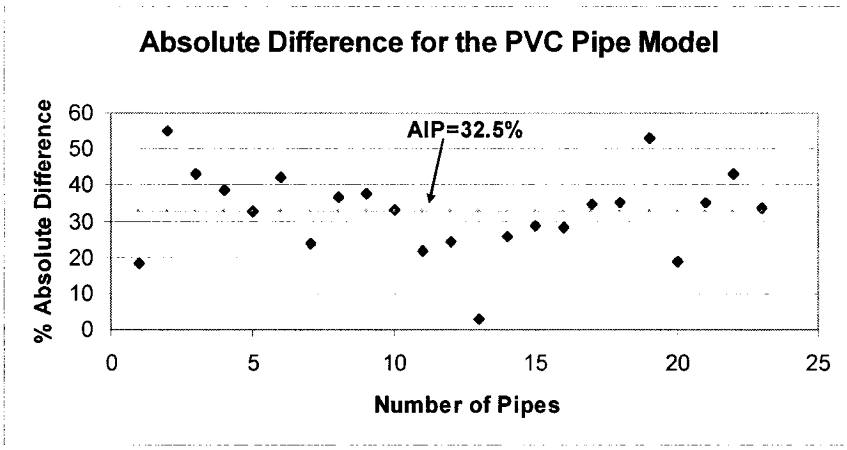

Figure 5-22 Validation Chart for the PVC Pipe Model

According to the AVP, this model is 67.5% validated to the 20% of data that were randomly selected. The result is moderately satisfactory. Considering the limit of the data and the complex of deterioration itself, the result is acceptable.

5.3.5 Modeling for Hyprescon (Concrete) Pipes

Best subsets regression was conducted with LogR ($Log_{10}R$) as the dependent variable and L,A,S,L2,A2,S2,L×A,L×S,A×S, LogL,LogA and LogS as the independent variables. The best subsets regression was not able to take the full dependent variables for there were some correlations existing between these sets of variables. Figure 5-23 shows the Best Subsets Regression Results with the set of independent variables L2,L2,S2 removed. The best subset with 8 variables and a Mallows C-p of 8 was selected for a multiple regression. The regression results were shown in Figure 5-24. With level of significance, α, as 0.1, the dependent variables with p values more than 0.1 were removed from further regression trials.

Finally, the multiple regression was conducted between the dependent variable, LogR, and the independent variables, L,L×S and LogL, as shown in Figure 5-25.

```
Best Subsets Regression: LogR versus L,A,S,LogL,LogA,LogS,L*A,L*S,A*S
Response is LogR

                                                     L L L
                                                     o o o L L A
                             Mallows                 g g g * * *
Vars  R-Sq  R-Sq(adj)            C-p        S  L A S L A S A S S
   1  78.7       78.0           -0.2  0.19816        X
   1  48.5       46.9           40.6  0.30826  X
   2  80.1       78.8           -0.1  0.19462      X X
   2  80.1       78.8           -0.1  0.19463        X   X
   3  81.3       79.3            0.3  0.19231  X     X       X
   3  80.8       78.8            0.9  0.19456        X   X X
   4  81.5       78.8            2.1  0.19466  X     X     X X
   4  81.4       78.8            2.1  0.19477  X     X       X X
   5  82.5       79.2            2.7  0.19283  X X   X       X X
   5  81.9       78.5            3.5  0.19603  X   X X X     X
   6  82.8       78.8            4.3  0.19485  X X   X     X X X
   6  82.5       78.4            4.7  0.19634  X X X X       X X
   7  82.8       78.0            6.3  0.19843  X X   X X   X X X
   7  82.8       77.9            6.3  0.19869  X X   X   X X X X
   8  83.0       77.3            8.0  0.20139  X X X X   X X X X
   8  82.9       77.2            8.1  0.20193  X X X X X   X X X
   9  83.0       76.3           10.0  0.20569  X X X X X X X X X
```

Figure 5-23 Best Subsets Regression of Hyprescon Pipes

```
Regression Analysis: LogR versus L, A, S, L*A, L*S, A*S, LogL, LogS

The regression equation is
LogR = 15.2 + 0.0250 L - 0.114 A + 0.0164 S + 0.000115 L*A - 0.000174 L*S
       + 0.000699 A*S - 0.974 LogL - 7.2 LogS

Predictor         Coef     SE Coef      T      P
Constant         15.17       22.92   0.66  0.514
L              0.02497     0.01549   1.61  0.120
A             -0.11369     0.08801  -1.29  0.209
S              0.01644     0.02840   0.58  0.568
L*A          0.0001151   0.0001448   0.79  0.435
L*S         -0.0001744   0.0001033  -1.69  0.104
A*S          0.0006993   0.0005390   1.30  0.207
LogL           -0.9744      0.1495  -6.52  0.000
LogS             -7.16       12.35  -0.58  0.567

S = 0.201386   R-Sq = 83.0%   R-Sq(adj) = 77.3%

Analysis of Variance

Source          DF       SS       MS      F      P
Regression       8  4.74947  0.59368  14.64  0.000
Residual Error  24  0.97335  0.04056
Total           32  5.72282

Source  DF   Seq SS
L        1  2.77703
A        1  0.13027
S        1  0.03879
L*A      1  0.03389
L*S      1  0.01014
A*S      1  0.03457
LogL     1  1.71114
LogS     1  0.01364
```

Figure 5-24 1st Multiple Regression for Hyprescon Pipes

```
Regression Analysis: LogR versus L, L*S, LogL

The regression equation is
LogR = 1.81 + 0.00593 L - 0.000028 L*S - 0.958 LogL

Predictor          Coef       SE Coef       T      P
Constant         1.8093        0.1668   10.84  0.000
L              0.005934      0.003030    1.96  0.060
L*S         -0.00002802    0.00001496   -1.87  0.071
LogL            -0.9580        0.1360   -7.04  0.000

S = 0.192310   R-Sq = 81.3%   R-Sq(adj) = 79.3%

Analysis of Variance

Source          DF      SS      MS      F      P
Regression       3  4.6503  1.5501  41.91  0.000
Residual Error  29  1.0725  0.0370
Total           32  5.7228

Source  DF  Seq SS
L        1  2.7770
L*S      1  0.0391
LogL     1  1.8342
```

Figure 5-25 Final Multiple Regression for Hyprescon Pipes

Hyprescon Pipe Model Prior to Testing of Significance

The developed model for the Hyprescon Pipes in Figure 5-20 has the following form:

$$Log_{10}\mathbf{R} = 1.81 + 0.00593\,\mathbf{L} - 0.000028\,\mathbf{L{\times}S} - 0.958\,Log_{10}\mathbf{L} \quad \textbf{.....5-5}$$

R-Sq = 81.3%   R-Sq(adj) = 79.3%

Testing for Significance of Hyprescon Pipe Model

Same testing of significance procedures was done to this model, and the details of the testing are shown below.

F Test

Based on Figure 5-25, because the Test Statistic F= 41.91>F_α= $F_{0.1}$ = 2.222486 (Obtained from Microsoft Excel), or, the p-value=0.000<α=0.1, the level of significance chosen for the present study, the hypothesis H_0 (β_i=0) can be rejected,

and H_a: (one or more of the parameters are not equal to zero) is true. A significant overall relationship is present for the Model in Equation 5-5.

t Test

Based on Figure 5-25, the values of Test Statistic $t_i = b_i/S_{bi}$ and p statistics are as follows:

t_1=1.96 p_1=0.060, t_2= -1.87 p_2=0.071, t_3= -7.04 p_3=0.000

Because $t_1, t_2, < -t_{\alpha/2}$=1.699127 (Obtained from Microsoft Excel), or, all p-values p_1, p_2,p_3<α=0.1, the hypothesis H_0 (β_i=0) can be rejected, and H_a ($\beta_i \neq 0$) is true. A significant individual relationship is present for the Model in Equation 5-5.

According to the above F test and t test results, the Hyprescon Pipe Model has both an overall statistical significance and individual statistical significance. Hence, the model can go through the validation process.

Hyprescon Pipe Model Validation

Same validation procedures as the above were carried out. The validation was based on the 20% of data that were randomly selected. The results are as follows:

$$AIP = (\sum_{i=1}^{n} |1-(E_i/C_i)|\ )/n = 3.8/8 = 50\%$$

$$AVP = 1-AIP = 1-50\% = 50\%$$

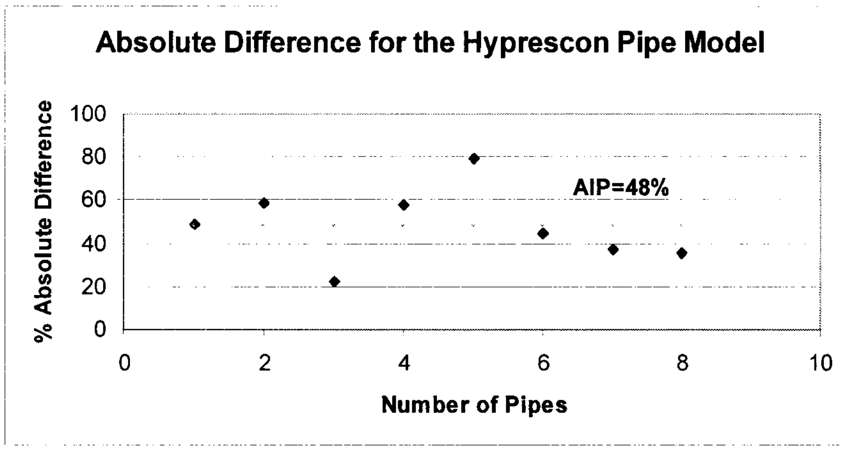

Figure 5-26 Validation Chart for the Hyprescon Pipe Model

Figure 5-26 shows the absolute differences ($|1-(E_i/C_i)|$ for the Hyprescon Pipe Model. According to the AVP, this model is 50% validated to the 20% of data that were randomly selected. The result is less satisfactory compared to others in the above. Considering the limit of the data for the Hyprescon pipes, only 8 data points (pipes) are used for validation, which may have caused the low AVP. Thus, the validation is considered to be acceptable.

Table 5-8 Summary of Developed Models

Material	Total Number of Data Points	Number of Data Points for Regression	Number of Data Points for Validation	Model Equation	R-Square (%)	Adjusted R-Square (%)	Testing of Significance (α=0.1)	Average Validity Percent (%)
Grey Cast Iron	476	381	95	$Log_{10}\mathbf{R} = 4.85-0.0206\mathbf{A}+0.000245\,\mathbf{A}^2 +0.00281\mathbf{S}-0.905Log_{10}\mathbf{L}-1.40\,Log_{10}\mathbf{S}$	68.9	68.5	Good	60.8
Ductile Iron (Not Lined)	187	149	38	$Log_{10}\mathbf{R} = 1.83-0.911Log_{10}\mathbf{L}$	65.0	64.8	Good	57.9
Ductile Iron (Lined)	186	149	37	$Log_{10}\mathbf{R} = 3.36 + 0.000150\,\mathbf{L}\times\mathbf{A} - 1.11\,Log_{10}\mathbf{L} - 0.646\,Log_{10}\mathbf{A} - 0.254\,Log_{10}\mathbf{S}$	71.5	70.7	Good	64.3
PVC	136	113	23	$Log_{10}\mathbf{R} = 2.69 - 0.898\,Log_{10}\mathbf{L} - 0.745\,Log_{10}\mathbf{A}$	78.9	78.4	Good	67.5
Hyprescon	47	39	8	$Log_{10}\mathbf{R} = 1.81 + 0.00593\,\mathbf{L} - 0.000028\,\mathbf{L}\times\mathbf{S} - 0.958\,Log_{10}\mathbf{L}$	81.3	79.3	Good	50.0

Table 5-9 Summary of Uses, Advantages and Limitations of the Existing and Developed Models

Model	Uses and Advantages	Limitations
Shamir and Howard (1979)	1. Used to predict break rates of homogenous pipe groups in a future year; 2. Easy to implement if homogeneous pipe group can be formed and can be used for economic analysis	1. Considered only time as the independent variable; 2. Homogeneous group of pipes may be difficult to be formed
Walski and Pelliccia (1982)	Same as Shamir and Howard (1979) Model	Same as Shamir and Howard (1979) Model
Clark et al. (1982)	First identified two stages of a pipe's deterioration: number of years until a pipe's first repair, and cumulative number of repairs after first repair	1. Relatively low R squares (0.23 & 0.45); 2. Applied to long pipes: typical value given for length of pipe in highly corrosive soil is 792 meters
McMullen (1982)	First considered soil corrositivity, PH, and redox potential in predicting number of years until a pipe's first break	1. Data are normally not available; 2. Soil conditions may change with time. However, continuous monitoring of such parameters could be impractical.
Jacobs and Karney (1994)	1. Used to estimate the probability of a day without any breaks in a network; 2. First defined independent breaks, and found such breaks are more uniformly distributed along a pipe network	1. Need exact break dates and locations to determine whether a break is independent or not; 2. Only applied to Winnipeg data
Proportional Hazards Models (Marks, 1985; Andreou et al.,1987a & b; Marks et al., 1987)	Very robust theoretical basis and used to estimate time durations between consecutive breaks; the prediction can be extended to individual pipes	1. More data are needed to establish good pipe failure hazards functions; 2. Lack of data in most municipalities has limited their use; 3 For two-stage models, the second stage assumes a constant hazards function, which means after second break, a pipe does not age. This may have ignored the fact corrosion may always exist.
Accelerated Lifetime Model (Lei, 1997)	Analogous to the Proportional Hazards Models but to predict time to next failure	Need complete data and expertise to apply
Lifetime Probabilistic (Survival) Model (Hertz, 1996)	Estimated useful life of homogenous group of pipes; good for financial needs analysis	1. Applied only to homogenous group of pipes; 2. Pipes may be replaced before reaching their useful lives due to various reasons
Semi-Markov Model (Gustafson and Clancy,1999)	Analyzed mean times until first breaks, and inter-break times	Inadequate for predicting future breaks
Artificial Neural Network Model (Sacluti et al.,1998)	Analyzed temperature (water and ambient), rainfall, operating pressure and historical data on pipe breaks against cumulative breaks of pipe group	1. Only applied to cumulative number of breaks of a pipe group. 2. ANN may not be able to pin point pipe breaks (Zhang, 2005)
Annual Break Rate Models (developed in the present research)	1. Analyzed the annual break rates of individual pipes of different materials versus pipe length, age and diameter; 2. Predict annual break rates can be used to estimate a pipe's near future number of breaks	1. The models are developed based on 15 years of break data of one municipality's water main distribution network; 2. Soil and corrosion protection (for metallic pipes) are not considered due to unavailability of data; 3. Assumed averaged break rates will continue until the near future; 4. Validation results are moderately satisfactory

5.3.6 Sensitivity Analysis of Developed Models

A summary of the developed models can be referred to Table 5-8. It shows the number of data points (individual pipes) used for each model, and the equations obtained from regression, R squares and validation results.

Table 5-9 summarizes the uses, advantages and limitations of the existing models and the newly developed models. The models developed in the present research focus on predicating the annual break rates of individual water mains, which is different from the existing models that forecast the break rate(s) of homogenous group of pipes for a future year or future years.

A sensitivity analysis has been done to check how annual break rates derived from the models given above may affect the annual break rate by adjusting certain variables while holding other variables fixed, where applicable, according to the developed models. The annual break rates versus pipe length and pipe age are presented in the following sections.

5.3.6.1 Annual Break Rate versus Pipe Length

Figure 5-27 shows a comparison of the annual break rates versus pipe lengths (between 20 to 200 meters) for the individual Grey Cast Iron, Ductile Iron (Not Lined), Ductile Iron (Lined), PVC and Hyprescon pipes that are 150 mm in diameter and 25 years of age. All pipes show a decreasing trend in annual break rate as the lengths of the pipes become larger. With the pipes' lengths less than

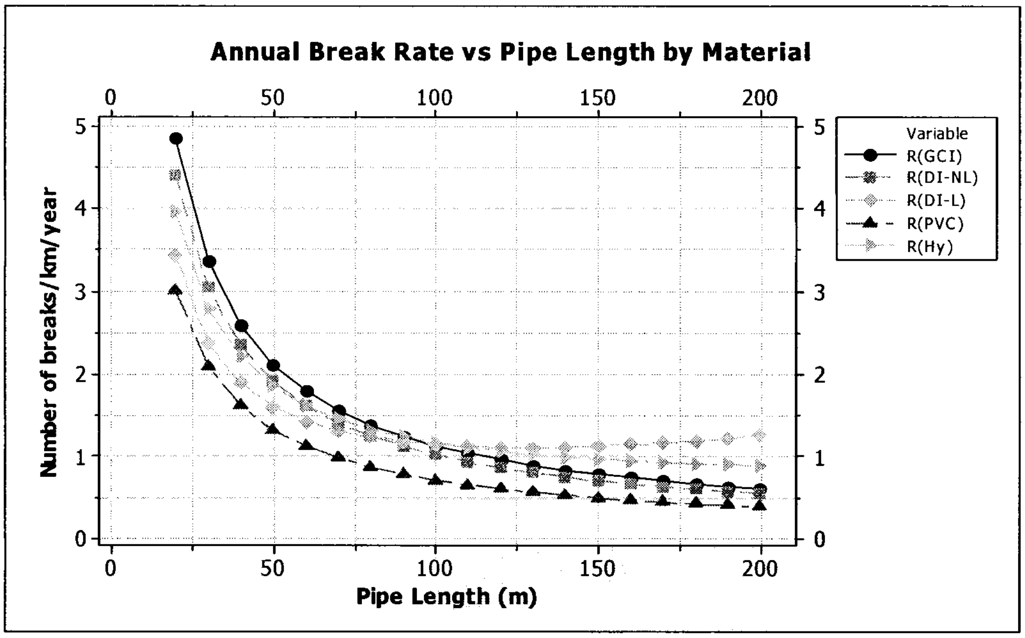

Figure 5-27 Annual Break Rate versus Pipe Length Comparison by Material

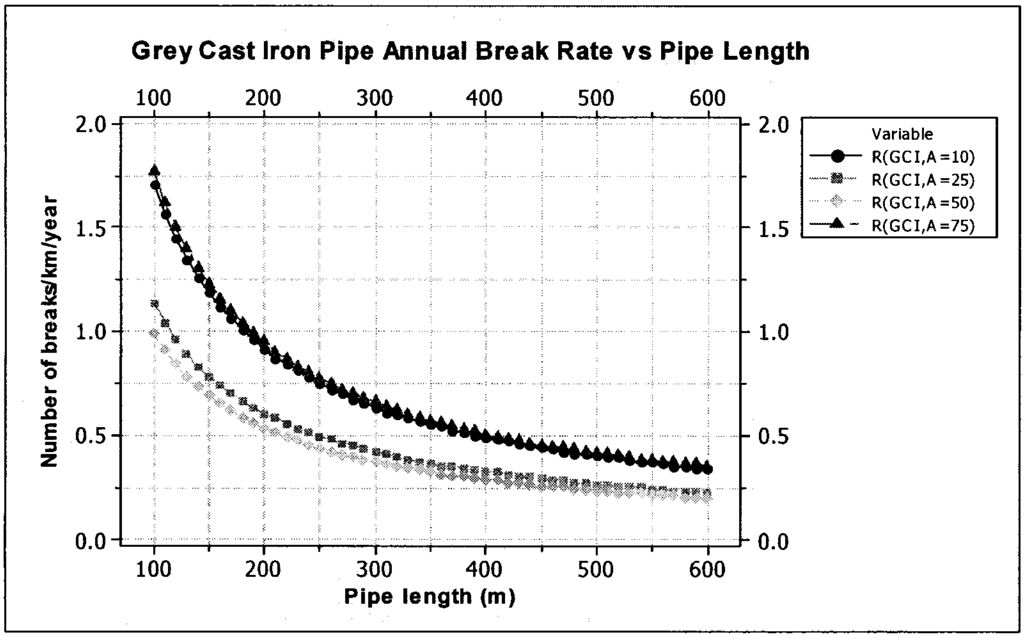

Figure 5-28 GCI Pipes of Different Ages Annual Break Rate versus Pipe Length

100 m, the Grey Cast Iron pipes have a higher annual break rates than other pipes. The PVC pipes have the lowest annual break rates compared to others.

Figure 5-28 shows that as the lengths of the individual, 150mm Grey Cast Iron pipes increase from 100 to 600 meters, the pipes have decreasing annual break rates. It should be noted that the model shows that the 75-year old pipes have break rates similar to those of the 10-year old pipes with different pipe lengths; the 25-year old pipes have break rates similar to those of 50-year old pipes. The annual break rates of the 75-year and 10-year old pipes are slightly higher than those of the 25-year and 50-year pipes. Perhaps the pipes of older ages do not always show higher annual break rates than the pipes of younger ages because different surrounding environments may exist.

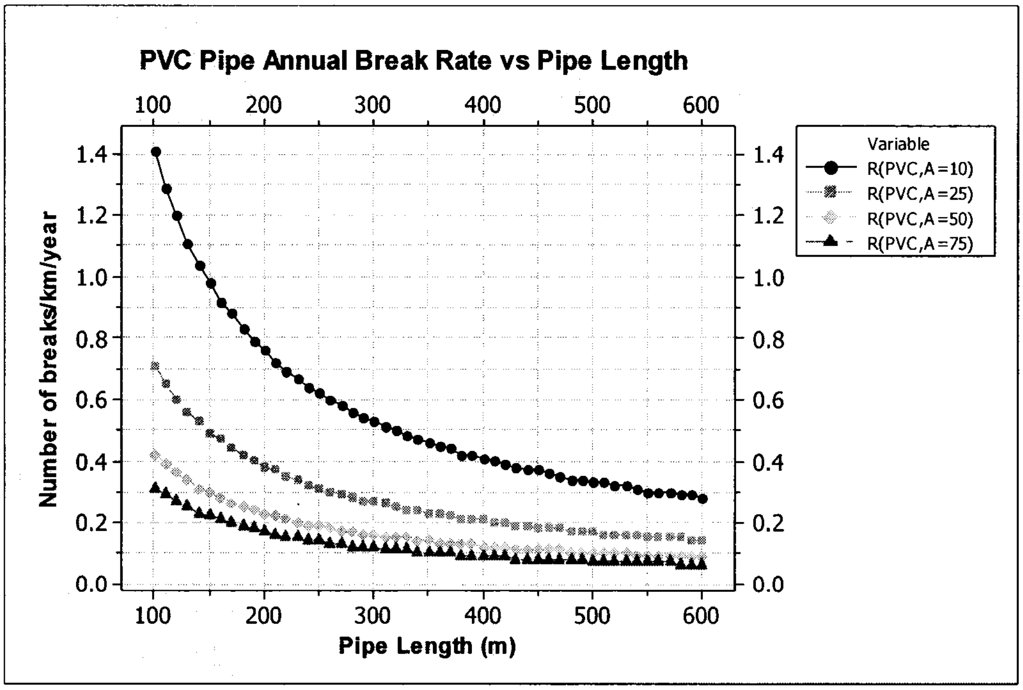

Figure 5-29 PVC Pipes of Different Ages Annual Break Rate versus Pipe Length

Figure 5-29 shows a trend that is similar to that of the Grey Cast Iron pipes; it shows decreasing annual break rates when increasing pipe lengths (between 100 to 600 meters) for the individual, 150mm PVC pipes. However, this figure shows that the younger pipes have higher annual break rates compared with the older pipes, probably because most of the PVC pipe breaks resulted from the poor quality of installation rather than from the aging of the pipes.

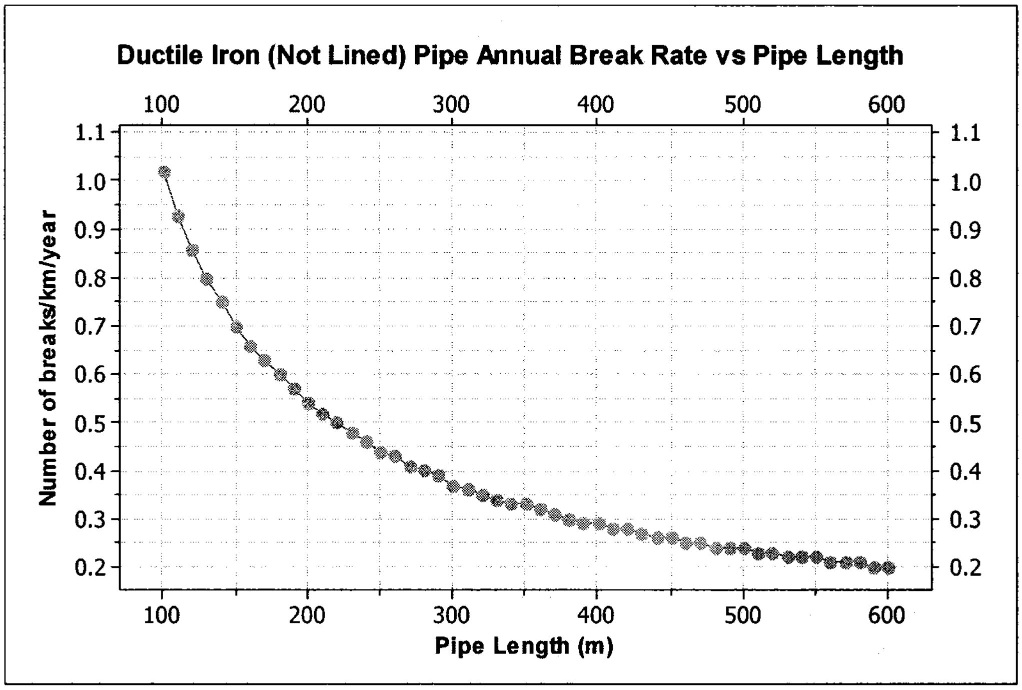

Figure 5-30 Ductile Iron (Not Lined) Pipe Annual Break Rate versus Pipe Length

Figure 5-30 shows that the individual Ductile Iron (Not Lined) pipes also have decreasing annual break rates when increasing the pipe lengths from 100 to 600 meters. It should be noted that for the Quebec data, the age or the pipe diameter seem to have less impact on the annual break rates of the Ductile Iron (Not Lined) pipes. The Model presents only pipe length as the predictor that is statistically significant. Limited data has probably caused this Model to be different compared to the others.

As can been from the above Figure 5-27 of the annual break rates versus the pipe lengths, when the pipes are chosen to be 150 mm in diameter, and 25 year of age, the annual break rates are solely affected by the pipe lengths. Figure 5-27 shows that a 200-m pipe always has a higher annual break rate than a 50-m pipe of any material specified here. Similar cases exist in Figure 5-28 for the Grey Cast Iron pipes of different ages, in Figure 5-29 for the PVC pipes of different ages, and in Figure 5-30 for the Ductile Iron (Not Lined) pipes. Therefore, it is difficult to have a fixed annual break rate (or a critical annual break rate) to determine a pipe's condition. This is contrary to what is generally understood in municipalities that the annual break rate is one of the important parameters to record and to use. In other words, it is probably inappropriate to use the number of breaks/km/year as one of the controlling factors in the condition rating analysis for individual pipes, unless the lengths of those pipes are similar. The annual break rate is probably good for macro benchmarking purposes only. For example, it can be used to compare the water main network performance according to the break history of different municipalities, or to compare the performance of water main pipe groups based on pipe material within a municipality.

To further study the annual break rates versus pipe length. The scatter plots of the total number of breaks and annual break rates versus pipe lengths for the individual pipes of different pipe materials in the Quebec data are plotted in the following sections.

Figure 5-31 shows that the scatter plots of the annual break rates of the individual water mains versus their pipe lengths for the Grey Cast Iron, Ductile Iron (Not Lined), Ductile Iron (Lined) and PVC pipes in the Quebec data. For all pipes of lengths less than 50 meters, the annual break rates are higher than those of pipes of larger lengths. The annual break rates are very much correlated to the pipe lengths according to these scatter plots.

Figure 5-32 gives the scatter plots of the total numbers of breaks of the individual water mains versus their pipe lengths for the Grey Cast Iron, Ductile Iron (Not Lined), Ductile Iron (Lined) and PVC pipes in the Quebec data. It can be observed that the total numbers of breaks of the individual water mains are not correlated with the individual pipe lengths.

Figure 5-33 shows the scatter plots of the total numbers of breaks and annual break rates of the individual water mains versus their pipe lengths for the Hyprescon pipes in the Quebec data. It can be observed that the total numbers of breaks of the individual water mains are not correlated with the individual pipe lengths, while the annual break rates have some correlation with the individual pipe lengths of the Hyprescon pipes.

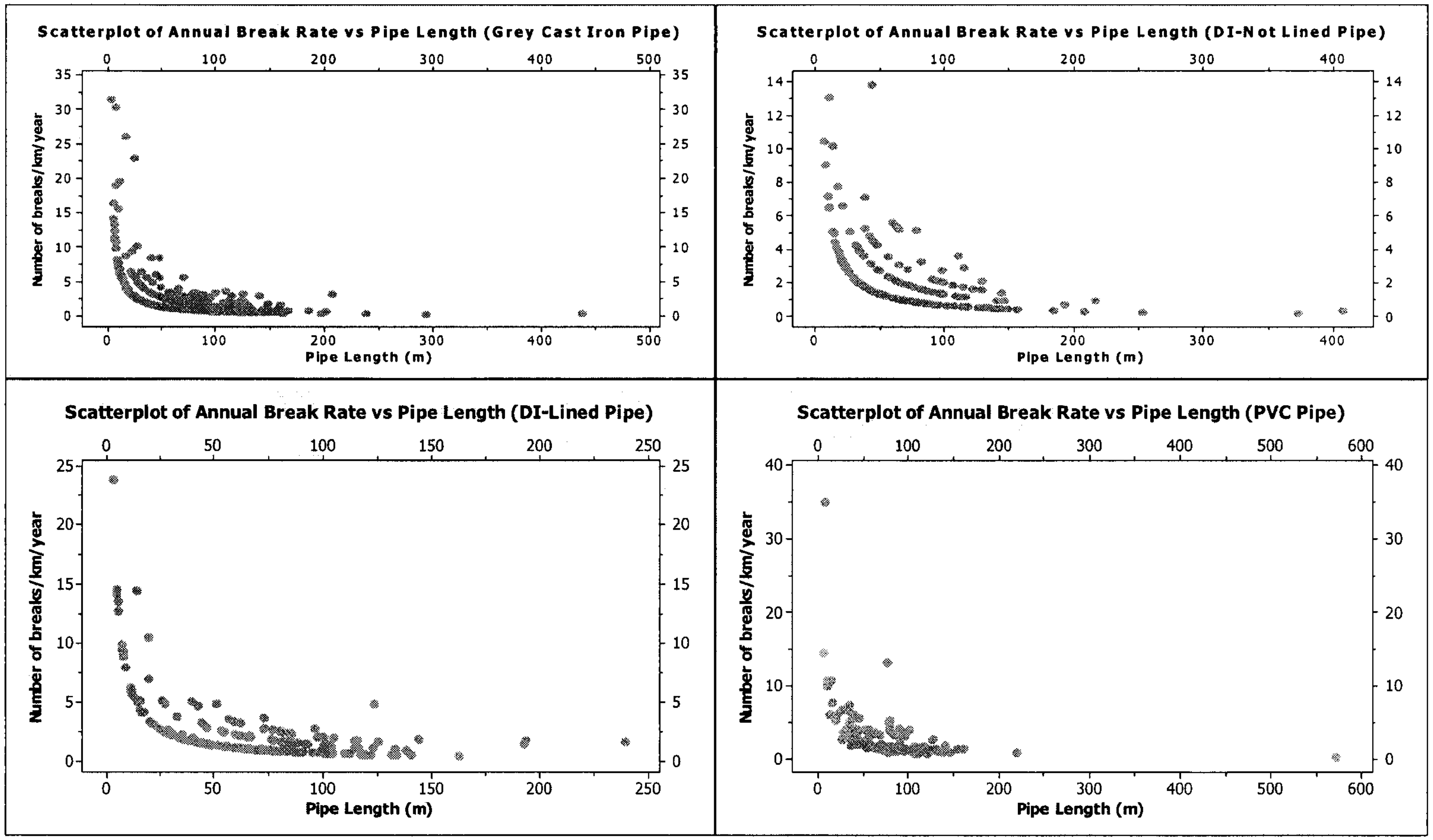

Figure 5-31 Scatter Plots of Annual Break Rate versus Pipe Length (GCI, DI-L, DI-NL and PVC Pipes)

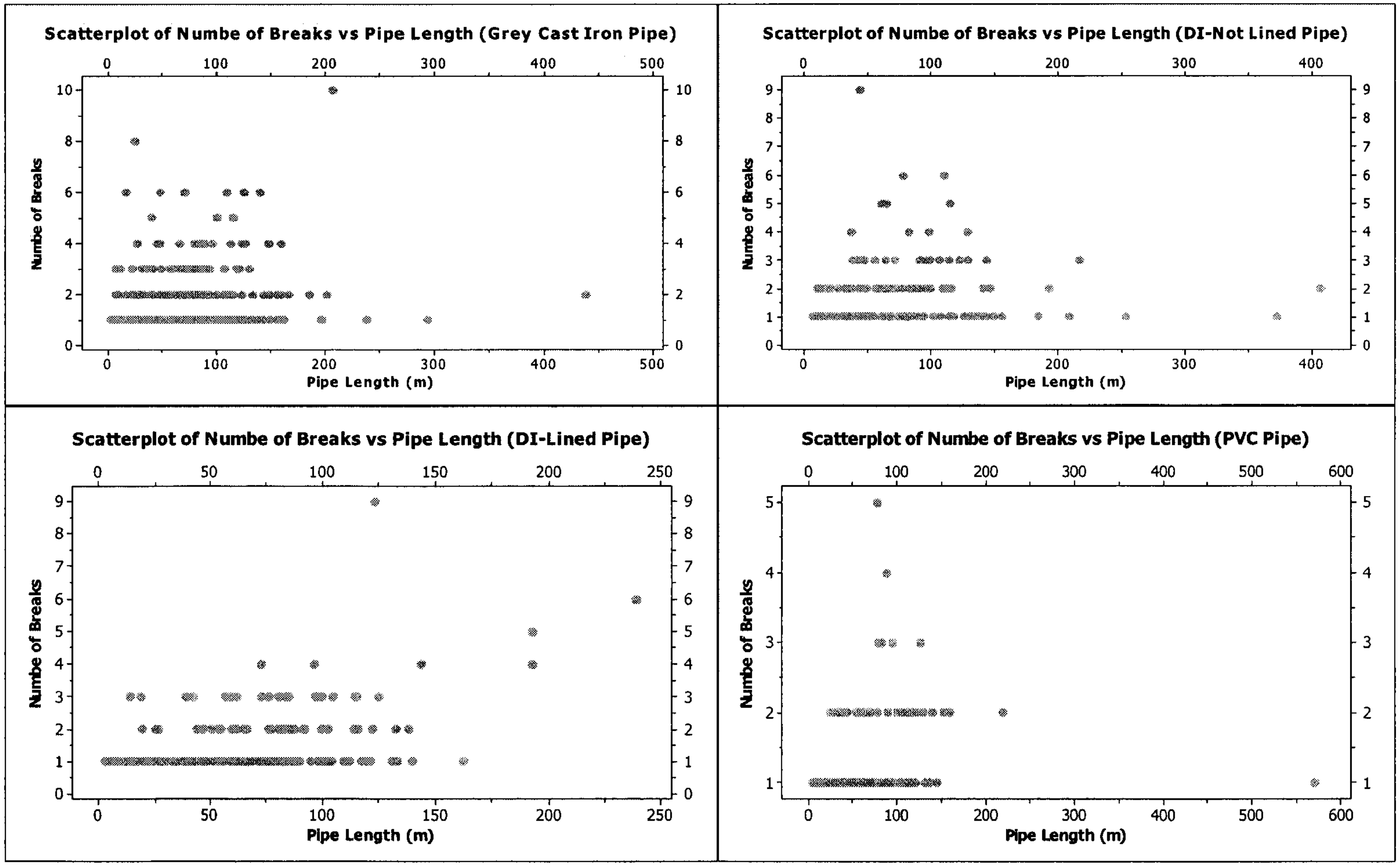

Figure 5-32 Scatter Plots of Number of Breaks versus Pipe Length (GCI, DI-L, DI-NL, and PVC Pipes)

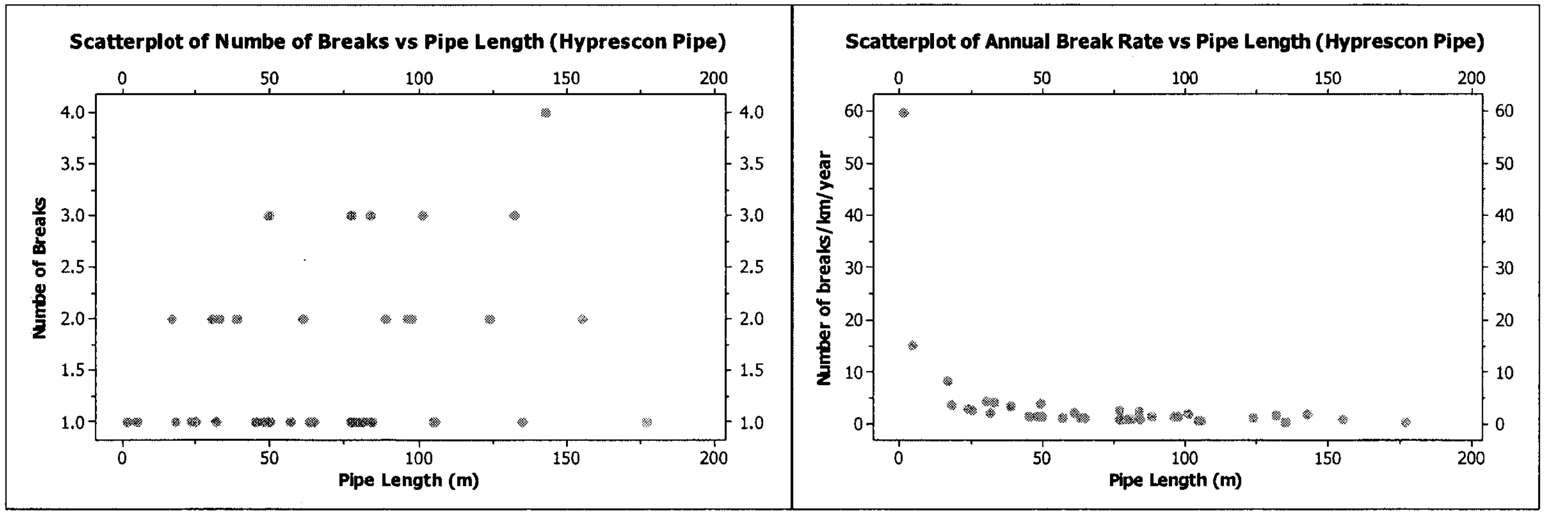

Figure 5-33 Scatter Plots of Number of Breaks and Annual Break Rate versus Pipe Length (Hyprescon Pipes)

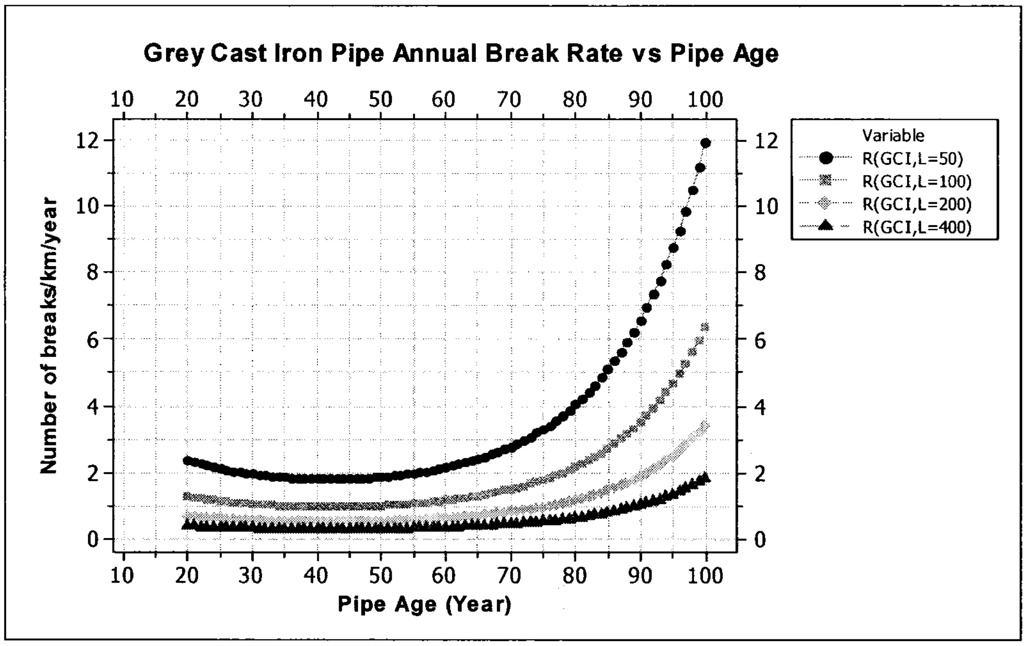

Figure 5-34 GCI Pipes of Different Lengths Annual Break Rate versus Pipe Age

5.3.6.2 Annual Break Rate versus Pipe Age

Figure 5-34 shows that the 150mm Grey Cast Iron pipes that are 50, 100, 200, and 400 meters in length all have increasing annual break rates as ages increase, according to the Grey Cast Iron Pipe Model. The pipes of shorter lengths have higher annual break rates than do those of longer lengths.

Figure 5-35 shows that the 150mm PVC pipes that are 50, 100, 200, and 400 meters in length all have decreasing annual break rates as ages increase, according to the PVC Pipe Model. The pipes of shorter lengths still have higher annual break rates than do those of longer lengths. The decreasing trend may result from the breaks associated with pipes of younger ages, rather than from the breaks of pipes of older ages in Quebec. It may be because there are few PVC pipes of older ages. On the other hand, in general, PVC pipes may have different deterioration patterns compared to metallic pipes in water distribution.

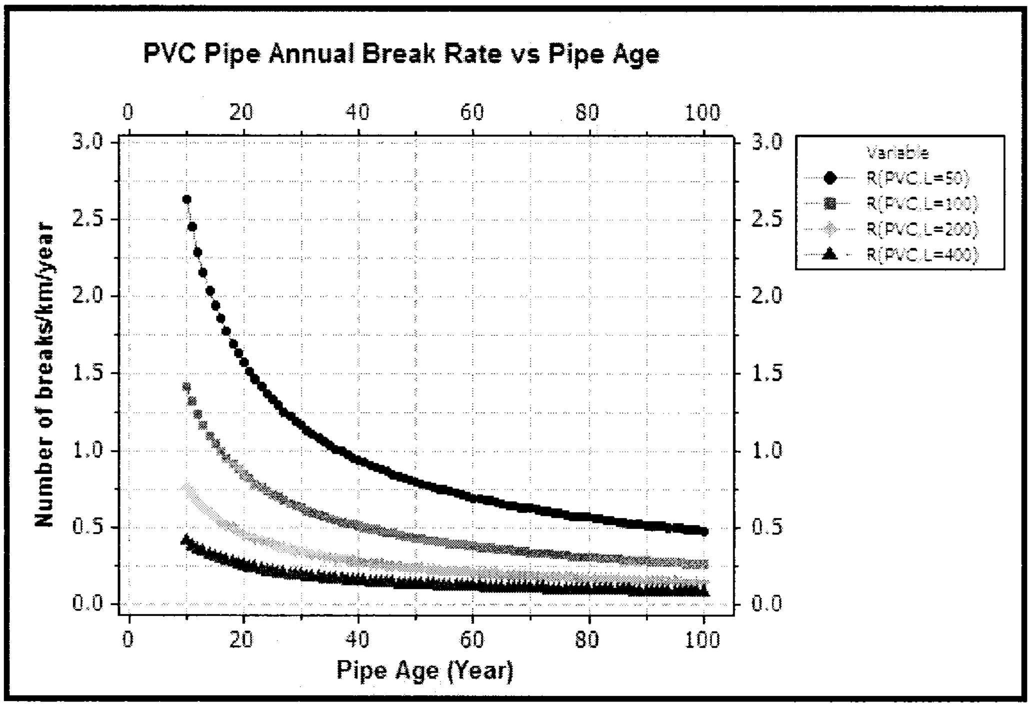

Figure 5-35 PVC Pipes of Different Lengths Annual Break Rate versus Pipe Age

Figure 5-36 shows the annual break rates of the 100-m pipes of different diameters versus pipe ages (from 30 to 100 year). Figure 5-37 shows a more detailed plot for the pipe ages between 30 and 80 years. The 100mm pipes have the highest annual break rates compared to others when they are of the same ages. The 300mm and 150mm pipes have similar annual break rates, as do the 200mm and 250mm pipes.

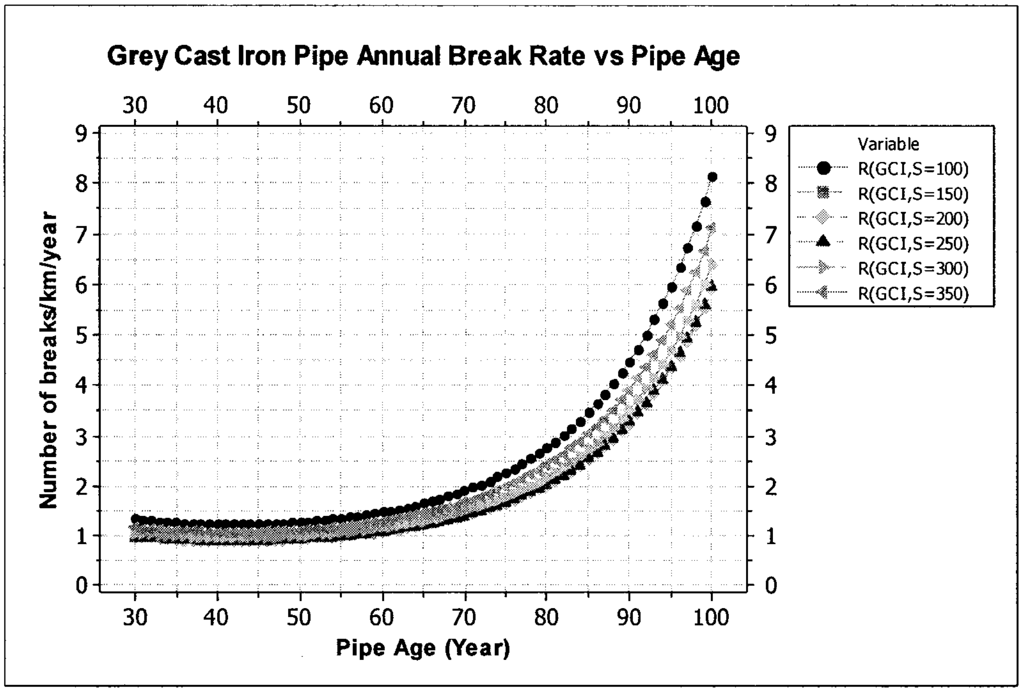

Figure 5-36 GCI Pipes of Different Sizes Annual Break Rate versus Pipe Age

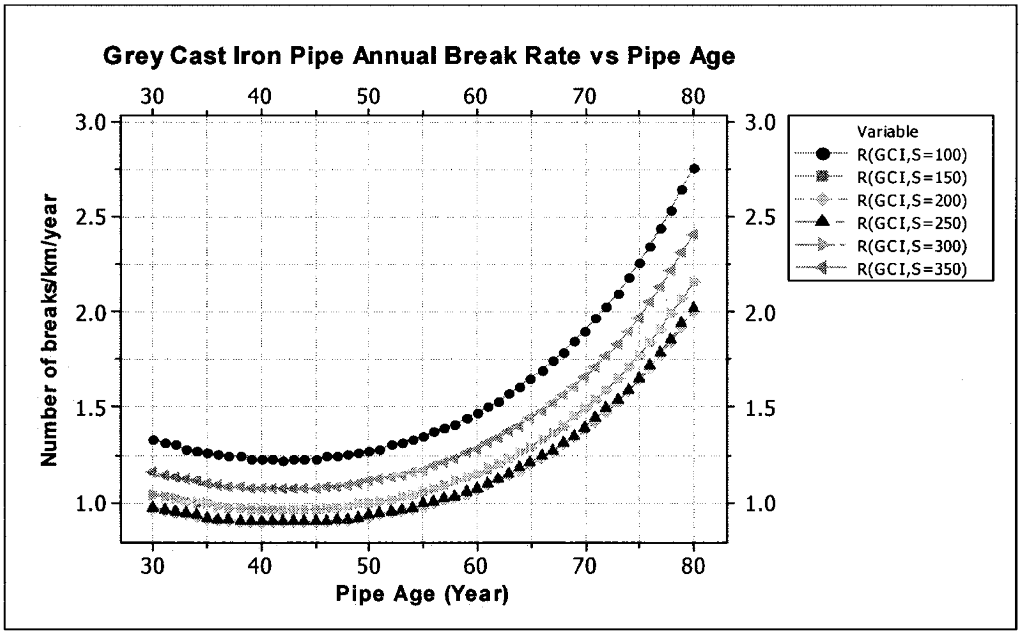

Figure 5-37 GCI Pipes of Different Sizes Annual Break Rate versus Pipe Age

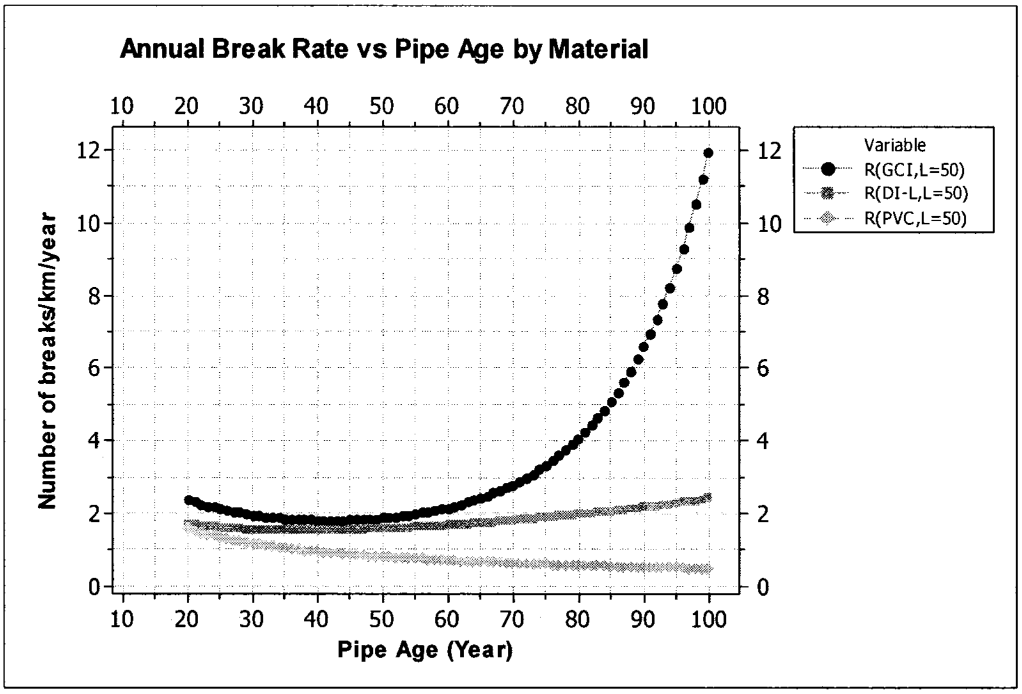

Figure 5-38 Annul Break Rate versus Pipe Age by Material(L=50)

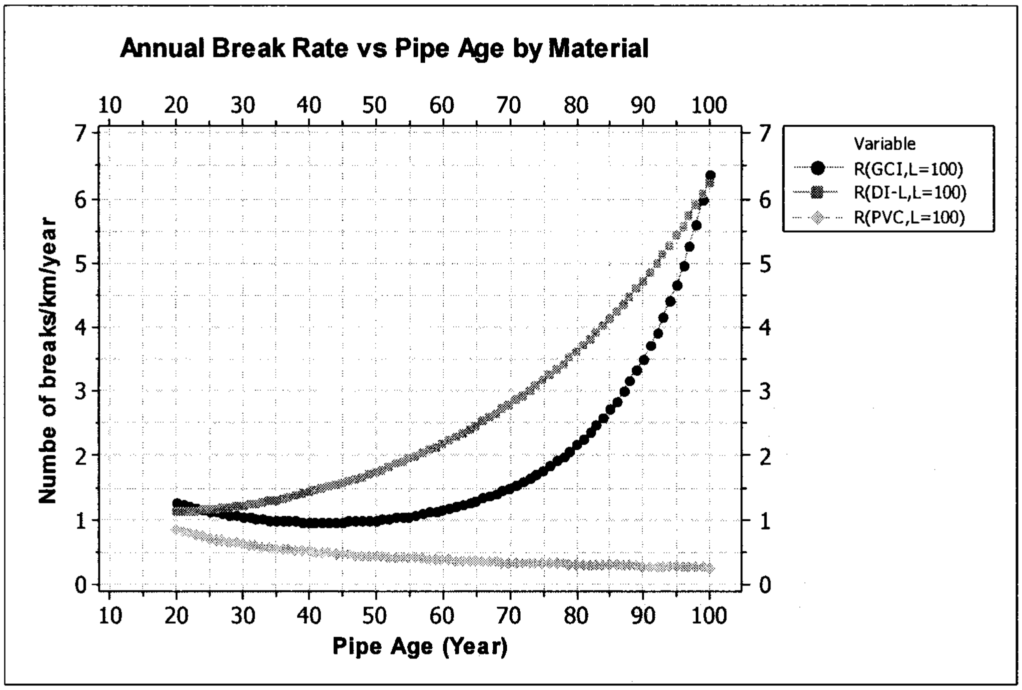

Figure 5-39 Annual Break Rate versus Pipe Age by Material (L=100)

Figures 5-38 and 5-39 show the annual break rates of the 150mm Grey Cast Iron, Ductile Iron (Lined), and PVC pipes versus pipe ages. The 50-m Grey Cast Iron pipes have higher annual break rates than the Ductile Iron (Lined) pipes of the same ages. The 100-m Ductile Iron (Lined) pipes have higher annual break rates than the Grey Cast Iron pipes when the pipes are of the same ages. Both these two type of pipes show a trend of increasing annual break rates when pipe ages increase, while the PVC pipes has the opposite trend. The complex process of water main deterioration and the specific water main environments in Quebec may have caused these differences.

5.4 Model Limitations and Summary

These models have been developed based on water main break data within a limited period of 15 years from 1987 to 2001. This has caused limitations in the developed models, which can be viewed as follows:

- The annual break rates for individual water mains in a pipe network have greatly been impacted by the lengths of these pipes. Thus, the annual break rate may not be a good parameter to be used to evaluate a water main's deterioration. In addition, as far as the evaluation of individual pipes' conditions is concerned, there are no industrial standards establishing how good or bad an annual break rate might be. Isenor and Lalonde (2003) use 50 breaks/100km/year (0.5 breaks/km/year) as a critical point for determining the physical index of a pipe for the City of Moncton. OFWAT (2002) uses 3-5 bursts/km/annum plus other measurements to indicate pipes near their end use of life. Therefore, even if the water main industry uses this parameter, the interpretation is very subjective.

- Since the annual break rates (number of breaks/km/year) are averaged values, it is not possible to consider the variance throughout the past individual years. Thus, the annual break rates that can be obtained through the developed models may be taken into the near future only based on the assumption that a similar deterioration process will continue. It is not possible to use the forecasted break rates to predict when the next failure is going to occur for a specific pipe.
- The R squares are improved when considering more second order terms or the interactions of first order terms in the multiple regression analysis. The R squares of the developed models are much better than those of several of the models in Chapter 2. However, more variables add difficulty to the explanation of those models according to engineering practices. For example, in the model for Ductile Iron (Not Lined) pipes, the pipe diameter and age related dependent variables are found to be less statistically significant, and are excluded from the models. '
- Past pipe repairs on the metallic pipes can have a major impact on their future deterioration patterns. However, these data are not available or may not be well maintained by the municipalities. The data about break repairs, and cathodic protection are not readily available either.
- The models obtained through regression analysis of the break data of individual pipes seem to have project-based characteristics, meaning that,

while regressions equations can be developed and a best-fit model can be selected for one municipality, it may be applicable for this municipality only. The models developed from the Quebec data do not have good validation results when used on the Moncton data. On the other hand, the unsatisfactory validation results for the Moncton data could be due to the quality of available Moncton data. So, whether these models can be applied to other municipalities' data should be studied further when more usable data are available.

- Lack of soil information could have caused variances in the model forms for the different pipe materials.

To summarize, even though the limitations of the annual break rates have been found in the present research work, these models are still valid. They can help Quebec predict the annual break rate of a given water main. The annual break rate can then be transferred into the number of breaks for the individual pipes, thereby allowing an economic analysis for budget planning.

5.5 Proposed Condition Rating Scale for Structural Deterioration

Shamir and Howard (1979), Walski and Pelliccia (1982) have used the exponential models in the economic analysis of water mains to determine the time when the selected homogeneous groups of water mains need to be replaced. Their analyses compare pipe repair costs versus pipe replacement costs to determine the best replacement timing. The existing condition rating practices have used more than break related factors (e.g. break rate, number of breaks, and break repair costs). The sensitivity analysis for the developed models indicates the annual break rate is not appropriate to be used as one of the controlling criteria when water mains of different lengths are considered. In general, condition rating practices reviewed in Chapter 2 tend to focus on performance as well as on the physical/ structural condition of water mains. The performance aspect might include water quality, water pressure, hydraulic capacity, leakage, and others. The physical/ structural condition may cover remaining pipe wall thickness, and other internal/ external condition of the pipes, for example, coating, lining, etc.

The condition rating system used by the City of Hamilton may arbitrarily overestimate the aging of a water main. For example, a water main 150 mm in diameter has a higher weight (0.6), than the pipes that are 200 mm (0.4), 250mm (0.2), 100 and 300 (0) in diameter. The lower the values, the lower the scores thereby affecting the overall properties index. This may not always be true. It could be because pipes 150 mm in diameter have the largest length in the pipe network and the largest number of breaks as well. The weights associated with pipe depths may cause the same problem. The impact of pipe depths towards water main deterioration may be related to traffic loading in general, even pipes at the same depths may have different traffic conditions, thereby resulting in a different impact on the deterioration of the individual pipes. Such a rating might be good for preliminary analysis, but more detailed action plans, such as sampling condition assessment, may be needed to verify the actual pipe condition before a decision on the pipe replacement is made.

OFWAT's (2002) approach on setting spatial indicators and the City of Edmonton's area approach may help identify water mains with a higher number of breaks or may facilitate considering water quality and customer complaints, etc. However, even OFWAT considers using different size for rural, urban, and sub-urban areas for this approach (Refer to Chapter 2). Within these areas, the density of water pipe networks still varies. Thus, such comparison by areas may not be completely valid.

Jacob and Karney's (1994) approach to defining independent breaks is worthy noting. Due to the limited data in the present research, an analysis can not be conducted of whether breaks are independent or not in the Quebec data. As far as the limitations of the annual break rates (number of breaks/km/year) are concerned, these rates could hardly be used to represent the water mains' conditions accurately, because the pipes of different lengths may be hard to compare. Parsons' (2005) proposal of using distance between two adjacent breaks may be a good substitute to indicate the structural deterioration of a water main. Parsons (2005) has used this approach to analyze the water main conditions. A four-year break data are used to determine each water main' rating (Refer to Table 2-6, Chapter 2). However, no justification is given on whether the 4-year break data are adequate. The optimized duration (how many years) of break data that one shall use to decide such a rating based on distance between breaks is still to be further studied and defined.

In this present research work, a new, preliminary condition rating scale for the structural deterioration of individual water mains based on only water main breaks is proposed by incorporating the independent break and distance between breaks, using concepts from Jacob and Karney (1994), and Parsons (2005).

Table 5-10 shows the summary of the proposed condition rating along with the descriptions and actions suggested.

According to Jacob and Karney (1994), independent breaks are defined as those breaks which occur more than 90 days after a previous break, or more than 20 meters from a previous break. In the present research work, a supplement is recommended to this definition, namely, that the independent breaks should include breaks occurring only on pipe walls of water main, since breaks resulting from the failure of joints or connections may not be due to the structural deterioration of a water main pipe itself. The breakage of joints or of connections may result from poor workmanship at the time of installation, unless such breaks can be confirmed to be due to the structural deterioration of the water main pipe; otherwise, they should not be categorized as independent breaks. Clark et al. (1982) have also excluded repairs on valves or lamps in their study. These independent breaks may be a better indicator of the structural deterioration of water mains, since they are randomly distributed in the water main network, according to Jacob and Karney (1994).

When two independent breaks (A and B) occur on a particular water main within a specific period of time, for example, from 1 to 2 years, as illustrated in Figure 5-40, it is highly likely that the pipe section between Break A and Break B has a deterioration condition similar to those of the two points where the pipe has breaks if the distance between Break A and Break B is relatively short. This pipe section may even extend to the left side of Break A and to the right side of Break B at some specific lengths. A sampling assessment for pipe wall thickness, leakage, or even soil corrositivity may be necessary to confirm the real condition of this water main before a decision about replacement may be made. At the same time, for a pipe of a long length, e.g. 1000 meters, replacement may not be carried out for the entire pipe length unless reliable samplings prove the need. In practice, for water main replacement based on breaks, only sections of the pipe (for example, one street block length of pipe) are often replaced. The distance between water main breaks concept may serve this practice better.

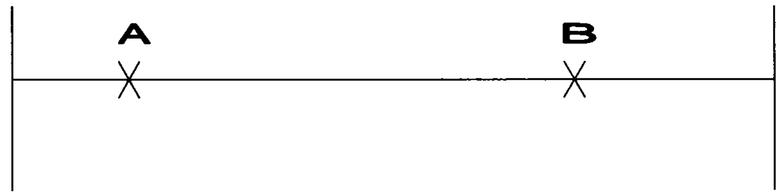

Figure 5-40 Two Independent Breaks on a Water Main

The scale proposed in Table 5-10 chooses a 50-meter distance between the independent breaks within one to two years as a baseline to determine whether a water main is in poor or even critical condition. If two or more independent breaks occur on a water main, but the distance of any of the two breaks is more than 100 meters, the water main is considered to be in a moderate condition. One or two consecutive years are chosen based on the assumption that if a water main is in poor or critical condition, the breaks associated with this water main tend to occur one after another in a reasonably short time period. However, the assumptions given above need to be further proved by analyzing more data, especially those data on pipe sections being replaced due to breaks. The anticipated data to be collected to enhance this condition rating analysis based on independent breaks and distance between two independent breaks are as follows:

- Lengths of pipe sections being replaced
- Number of breaks occurred to the pipe section
- Type of breaks
- Time of breaks
- Distances between breaks
- Whole pipe lengths (assuming sections of pipes being replaced)
- Date of pipe installed
- Pipe material and diameter,
- Environment data such as soil corrositivity.

Table 5-10 Proposed Condition Rating on Structural Deterioration of Water Mains

Condition Rating	General Evaluation	Condition Measurement	Actions to Take
1	Excellent	Like new with no breaks. The pipe is within 10% of designed service life	None
2	Good	The pipe has only minor breaks on joints or connections, and/ or the pipe is within 10-25% of its designed service life	Regular monitoring needed
3	Moderate	The pipe has one independent break a year, or the pipe has two or more independent breaks more than 100 meters apart in two consecutive years, and/ or the pipe is within 25-60% of its designed service life	Regular monitoring needed. May require sampling on pipe wall thickness or leakage detection.
4	Poor	The pipe has two independent breaks in one year or in two consecutive years less than 50 meters apart, and/ or the pipe is within 60-95% of its designed service life	Regular monitoring needed. Sampling on pipe wall thickness or leakage detection is required. Pipe may need replacement in the near future
5	Critical	The pipe has three or more independent breaks in one year or in two consecutive years with less than 50 meters apart, and/ or the pipe is 95-100% of or over its designed service life	Sampling on pipe wall thickness or leakage detection is required. Immediate replacement may be needed

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The present research work has thoroughly discussed the factors that affect the structural deterioration of water mains, the existing deterioration models, and condition rating practices. The existing deterioration models have been applied to municipal data with unsatisfactory results. Detailed descriptive statistical analysis has been conducted for Quebec data. Deterioration models based on break data of individual pipes of different materials have been developed to predict the annual break rate versus factors related to pipe diameter, length and age. The developed models have been proved to be statistically significant. Further discussion on the limitations of the developed models is presented. A preliminary condition rating scale based on only pipe breaks has been proposed for evaluating the structural deterioration of a water main.

- The existing exponential, deterministic model has produced unsatisfactory results when analyzing Quebec data because homogenous pipe groups are difficult to be identified/ formed. The models have assumed that such groups of pipes have same breakage patterns since they were installed, and that the same patterns will be carried into the future. For the Quebec data, none of the pipe groups formed have shown continuous increasing break rates from 1987 to 2001. For example, for the 23.45km, 150mm Ductile Iron (Not Lined) pipes installed in the 1950s, there is no break at all in the year 2001.

- According to the analysis of the developed models and the Quebec data, a pipe's length has great impact on the pipe's annual break rate. Pipes of shorter lengths that have higher annual break rates do not necessarily have more breaks compared to pipes of longer lengths, though the annual break rate has been widely used today. It was expected at the beginning of the present research that the annual break rates might be used for condition rating of water mains. However, the present research has suggested that the annual break rate (number of breaks/km/year) for individual water mains should be removed from the list of criteria that are used to evaluate the performance of individual water mains, unless these water mains are of similar lengths.
- The developed deterioration models have relatively satisfactory R squares, 68.9%, 65.0%, 71.5%, 78.4%, and 81.3% for the models of Grey Cast Iron, Ductile Iron (Not Lined), Ductile Iron (Lined), PVC, and Hyprescon pipes respectively, compared to the R squares of 23% and 47% for Clark et al.(1982) Models and 37.5% for McMullen (1982) Model. The models have identified statistically correlated factors that affect the annual break rates for each pipe material in Quebec. The average validity percents for the five developed models are 60.8%, 57.9%, 64.3%, 67.5%, and 50.0% respectively, which are reasonably satisfactory. The existing models given in literature have rarely mentioned the validation. The developed models can be used to forecast the annual break rates of individual water mains; the forecasted annual break rates can then to be transformed to the

numbers of breaks by multiplying the time period(e.g. 5 years). The numbers of breaks associated with the individual water mains can be used to project the near future maintenance/ repair costs in the time period specified.

- Independent breaks are more randomly distributed along the water main network (Jacob and Karney, 1994); the process needed to identify whether a pipe break is an independent break or not may help produce more reliable break records to exclude none structural related breaks (e.g. from joints, connections, valves, or previous break repairs). These independent breaks probably are more representative of the structural conditions of water mains, which should be used for rating of structural deterioration of water mains. The distance between breaks is able to help to identify pipe sections within a pipe, which are probably more risky towards further structural failures. It is also able to help eliminate the inability to use the annual break rate to compare the conditions of pipes of different lengths. Thus, with two concepts together, the structural condition of a water main can be better interpreted, though more study is needed to make the proposed condition rating scale usable.

6.2 Research Contributions

The present study has presented a detailed analysis for the structural deterioration of water mains, and for the existing condition rating practices of water mains. The major contributions are as follows:

- ❖ Review the existing condition rating practices used in municipalities and the deterioration models given in literature.
- ❖ Study the applicability of the existing models to current data sets.
- ❖ Develop new deterioration models in order to forecast annual break rates of individual pipes based on available information about pipe age, diameter, length, and break history.

6.3 Future Work

The development of deterioration models are based on limited data collected from one municipality. Therefore, there is a great potential for the present study to incorporate more data sets to further analyze the developed models and the structural deterioration of water mains. The following is a list of recommended future endeavors:

- ❖ Use data mining techniques to analyze Laval GIS data, which have not assigned breaks to individual pipes. Data mining might be able to make the associations possible, thus more detailed study on the deterioration of individual pipes can be conducted.
- ❖ Integrate soil and cathodic protection data into deterioration analysis of water mains of the City of Quebec to understand how these can affect the deterioration patterns of water mains.
- ❖ Expand efforts in the study of water main breaks by adding different categories, such as breaks due to joints of water mains, and by developing quantitative measuring methods on circumferential, longitudinal,

perforation, and other types of breaks. In other words, it may be very important to develop a possible severity measurement methodology on pipe breaks. The development of the severity measurement of water main breaks would be of great help if the measurements can be associated with the causes of breaks that can possibly be identified. The measurements may include repair costs, and impacts on the customers, e.g. durations of interruptions and repairs. The development of the measurements may refer to the sewer condition classification (UK Water Industry, 1993), though the sewer condition classification is based on physical inspection of a whole section of a sewer pipe, while the severity measurement for water main breaks may focus on only individual breaks.

- Integrate other statistical analyses such as survival analysis in predicting when the next failure may occur on specific pipes in order to further prioritize pipes that may break soon when more complete water main data are available.
- Incorporate sewer and road information (using GIS) into decision making of repair, rehabilitation, and replacement of water mains so that similar remediation actions can be carried out simultaneously to save resources (time and costs) and to improve the levels of services for municipal infrastructure as a whole.
- Incorporate weather and localization factors into deterioration models.

References

Al-Aghbar, A. (2005). "Automated Selected Trenchless Technology for the Rehabilitation of Water Mains." Master of Applied Science Thesis. Submitted to the Department of Building, Civil, and Environmental Engineering, Concordia University, Canada.

Al-Aghbar, A., Moselhi, O., and Lahaie, L (2005). " Trenchless Rehabilitation of Water Mains." In Proceedings of the 1st CSCE Specialty Conference on Infrastructure Technologies, Management and Policy. CSCE 2005 Conference, Toronto, Canada.

Anderson, D.R., Sweeney, D. and Williams T. A. (2002). "Statistics for Business and Economics." 8th Edition, South-Western, Mason, U.S., ISBN 0324066724.

Andreou, S.A. and Marks, D.H. (1986). "Maintenance Planning Strategies for Large Diameter Cast-iron Mains." AWWA Conference Synopsis, Denver, Colorado, U.S. pp. 365-372.

Andreou,S.A, Marks, D.H., and Clark, R.M. (1987a). "A New Methodology for Modeling Break Failure Patterns in Deteriorating Water Distributing Systems: Theory." Advance in Water Resources,10 (1),p.p.2-10.

Andreou,S.A, Marks, D.H., and Clark, R.M. (1987b). "A New Methodology for Modeling Break Failure Patterns in Deteriorating Water Distributing Systems: Applications." Advance in Water Resources,10(1),p.p.11-20.

AWWARF (1996). "Internal Corrosion of Water Distribution Systems." 2nd Edition, American Water Works Association, Denver, Colorado, U.S. ISBN 0898677599 Research.

AWWSC (2002). "Deteriorating Buried Infrastructure Management Challenges and Strategies". American Water Works Service Co., Inc. May 2002. http://www.epa.gov/OGWDW/tcr/pdf/infrastructure.pdf (17 September 2005)

Baer, N. (1998). "Buried Treasure." Journal of Canadian Consulting Engineer, v. 39, no. 2, March-April 1998, p.p. 41-43.

Bainbridge, K. (2004). "Applied Asset Management Strategies." INFRA 2004, Montreal, Canada. 15 November 2004.

Bremond,B. (1997). "Statistical Modeling as Help in Network Renewal Decision." European Commission Co-operation on Science and Technology (COST), Committee C3- Diagnostics of Urban Infrastructure, Paris, France.

C3 (1998). "Safe Water Delivered Safely." Chlorine Chemistry Council Online Knowledge Center. http://c3.org/chlorine_knowledge_center/safewater.html (9th April 2006)

Cameron, A. (2004). "Prioritization of Water Distribution Renewals." M.Eng. Project. Submitted to University of Alberta.

Cameron, A. (2005). "Prioritization of Water Distribution System Renewal Projects." In Proceedings of the 57th Annual Conference of the Western Canada Water and Wastewater Association, Saskatoon, Saskatchewan, Canada. October 16 – 19, 2005.

Clancy, D., Gustafson, J.M., and Higgins, L. (2002). "Economical Sewer Main Rehabilitation Utilizing ArcGIS and Dynamic Segmentation." 22nd Annual ESRI International User Conference, San Diego, CA, US. July 8-12, 2002.

Clark, R.M., Stafford, C.L., and Goodrich, J.A. (1982). "Water distribution systems :a spatial and cost evaluation." Journal of Water Resources Planning and Management Division, ASCE, 108(3), pp. 243-256.

Craun, G.F. and Calderon, R.L. (2001). "Waterborne Disease Outbreaks Caused by Distribution System Deficiencies." Journal of AWWA. Vol. 93, No. 9, pp. 64-75.

Doherty, B.J. (1990). "Controlling Ductile-iron Water Main Corrosion: A Preventative Maintenance Measure." Materials Performance, 29(1), pp. 22-28.

Eisenbeis, P. (1994). "Modelisation statistique de la prevision des defaillances sur les conduits d'eau potable." Ph.D. thesis, University of Louis Pasteur of Strasbourg.

Fortner, B. (1999). "Main Line Mending". Civil Engineering. July. pp. 42-45.

GITA (2002). "Geospatial Technology Report 2002: A Survey of Organizations Implementing Geospatial Information Technologies." Geospatial Information Technology Association. Aurora, CO, US.

Grau, P. (1991). "Problems of External Corrosion in Water Distribution Systems." Water Supply Congress, International Water Supply Association, International Reports, 9 (3/4), 5-1, 5-45.

Goutler, I.C., and Kazemi, A. (1988). "Spatial and Temporal Groupings of Water Main Pipe Breakage in Winnipeg." Canadian Journal of Civil Engineering, 15(1), pp. 91-97.

Goutler, I.C., Davidson, J. and Jacobs, P. (1993). "Predicting Watermain Breakage Rate." Journal of Water Resources Planning and Management, ASCE 119(4), pp. 419-436.

Greek, D. (1997). “Technological Fingers in the Dyke.” Professional Engineering, Nov. 1997.

Green, B.M., Johnson, F., and De Rosa, J. (1992). “In Situ Cathodic Protection of Existing Ductile Iron Pipes.” Materials Performance, 31(3), pp. 32-38.

Gummow, R.A. (1988). “Experiences With Water Main Corrosion.” Joint Annual Conference of the Ontario Section AWWA and OMWA, Denver, CO., US. American Water Works Association, London, Ontario, Canada. pp. 1-41.

Gustafson, J.M. and Clancy, D.V. (1999). “Modeling the Occurrence of Breaks in Cast Iron Water Mains Using Methods of Survival Analysis.” In Proceedings of the AWWA Annual Conference, Chicago, IL, US.

Halfawy, M.R., Pyzoha, D., and El-Hosseiny T. (2002). “An Integrated Framework for GIS-Based Civil Infrastructure Management Systems.” Proceedings of the CSCE 2002 Conference of the Canadian Society for Civil Engineers, Montreal, Canada, June 5-8.

Halfawy, M.R. (2004). “Municipal Infrastructure Investment Planning (MIIP).” NRC Client Report, B-5123.4, part 2, 2004.

Halfawy, M.R., Newton, L. and Vanier, D. (2005). “Municipal Infrastructure Asset Management Systems: State-of-the-Art Review.” IRC-NRC, Canada.

Hatfield (1987). “Metal Pipe Corrosion.” Internal Report Submitted to Melbourne Water, Melbourne, Australia. [Cited by Marvin, K. (1996)]

Herbert, H. (1994). “Technical and Economic Criteria Determining the Rehabilitation and/or Renewal of Drinking Water Pipelines.” Water Supply, 12 (3/4, Zurich), pp. 105-118.

Herz, R.K. (1996). “Aging Processes and Rehabilitation Needs of Drinking Water Distribution Networks.” Journal of Water SRT- Aqua, 45(5), pp. 221-231

Infraguide (2002). “Deterioration and Inspection of Water Distribution Systems.” A Best Practice by the National Guide to Sustainable Municipal Infrastructure. Issue 1.0, September 2002.
http://www.infraguide.ca/lib/db2file.asp?fileid=4209 (20 June 2005)

Isenor, G., Lalonde, E. (2003). “City of Moncton Water Main Transmission Distribution System Assessment Study.” Submitted to the City of Moncton, New Brunswick, Canada by Dillon Consulting Limited and Harfan Technologies. July 2003.

Jacobs, P. and Karney, B. (1994). “GIS Development with Application to Cast Iron Main Breakage Rate.” In the 2nd international conference on water pipeline systems. BHR Group Ltd., Edinburgh, Scotland.

Jarvis, M.J. and Hedges, M.R. (1994). “Use of Soil Maps to Predict the Incidence of Corrosion and the Need for Iron Mains Renewal.” Journal of Institution of Water Environment Management, 8, pp. 68-75.

Kettler, A.J., and Goulter, I.C. (1985). “An Analysis of Pipe Breakage in Urban Water Distribution Networks.” Canadian Journal of Civil Engineering, 12, pp. 286-293.

Kleinbaum, D.G. and Kupper L.L. (1978). “Applied Regression Analysis and Other Multivariable Methods.” Duxbury Press. ISBN 0-87150-355-7.

Kleiner, Y. and Rajani, B. (2001a). “Comprehensive Review of Structural Deterioration of Water Mains: Statistical Models”. Urban Water, 3(3), pp.131-150.

Kleiner, Y. and Rajani, B. (2001b). "Comprehensive Review of Structural Deterioration of Water Mains: Physically Based Models." Urban Water, 3(3), pp.151-164.

Lei, J. (1997). "Statistical Approach for Describing Lifetimes of Water Mains-Case Trondheim Municipality." SINTEF Civil and Environmental Engineering, Report No. 22F007.28, Trondheim, Norway.

Lewis, R. O. (1999). "A White Paper Review: History Of Use And Performance Of Copper Tube For Potable Water Service." Lewis Engineering and Consulting, Inc. http://www.wssc.dst.md.us/copperpipe/copperpipewp.cfm (9th April 2006)

Lim, E.L. and Pratti R. (2001). "Pipe Evaluation System (PIPES)." http://gis.esri.com/library/userconf/proc97/proc97/to350/pap346/p346.htm (29 June, 2005)

Marks, H.D. (1985). "Predicting Urban Water Distribution Maintenance Strategies: A Case Study of New Haven Connecticut." Reported submitted to US Environmental Protection Agency by the Department of Civil Engineering, M.I.T, Cambridge, Massachusetts, US.(Co-operative Agreement R8 1 0558-01-0).

Marks, H.D., Andreou, S., Jeffrey, L., Park, C. and Zaslavski, A. (1987). "Statistical Models for Water Main Failures." US Environmental Protection Agency (Co-operative Agreement CR8 1 0558) M.I.T. Office of Sponsored Projects No. 94211. Boston, MA, US.

Marvin, K. (1996). "Predicting the Failure Performance of Individual Water Mains." Research Report No. 114. Submitted to Urban Water Research Association of Australia, Melbourne, Australia. July 1996.

Minitab (2002), "Using Best Subsets Regression." Minitab Statguide, Version 5.1.2600.2180, Minitab Software Version 14.

McMahon, P. (1997). "Geographic Information System in the Construction Industry- an Underused Resource." Construction Papers, No. 82, the Chartered Institute of Building, Ascot, UK.

McMullen, L.D. (1982). "Advanced Concepts in Soil Evaluation for Exterior Pipeline Corrosion." In Proceedings of the AWWA Annual Conference, Miami, Florida, US.

Micevski T., Kuczera, G. and Coombes, P. (2002). "Makov Model for Storm Water Pipe Deterioration." Journal of Infrastructure Systems, ASCE Vol. 8. No. (2), 2002. pp. 49-56.

Morris, R.E. Jr. (1975). "The Distribution System, Manual of Water Utility Operation." Texas Water Utilities BD., Austin, Texas.

NRC (1996). "Why There Are More Water Main Breaks During Winter." Construction Innovation, Vol. 2 (1), 1996. http://irc.nrc-cnrc.gc.ca/pubs/ci/v2no1/v2no1_24_e.html (15 September 2005)

O'Day, K. (1982). "Organizing and Analyzing Leak and Break Data for Making Main Replacement Decisions." AWWA Journal, 74 (11), pp. 589-594.

O'Day, K. (1989). "External Corrosion in Distribution Systems." AWWA Journal, 81(10), pp. 45-52.

OFWAT (2002). "Maintaining Serviceability to Customers in England and Wales- Development of Spatial Indicators for Regulatory Reporting." http://www.ofwat.gov.uk/aptrix/ofwat/publish.nsf/AttachmentsByTitle/serv_spatial_may02.pdf/$FILE/serv_spatial_may02.pdf (30 September, 2005)

Parsons, D. (1999 a). “Asset Management in Water Distribution: Part 1.” Pipes & Pipelines International. Vol. 44, no. 2, pp. 5-14. Mar.-Apr. 1999

Parsons, D. (1999 b). “Asset Management in Water Distribution: Part 2.” Pipes & Pipelines International. Vol. 44, no. 3, pp. p 10p. 1999

Parsons, D. (2005). E mails. 20-22 September 2005. Telephone 0121 625 1484 derek.parsons@ofwat.gsi.gov.uk.

Pascal, O. and Revol, D. (1994). “Renovation of Water Supply Systems.” Water Supply Congress, International Water Supply Association, 12 ((1/2) Budapest), 6-3, 6-7.

Pelletier, G., Mailhot, A. and Villeneuve, J.P. (2003). “Modeling Water Pipe Breaks- Three Case Studies.” ASCE, Journal of Water Resources Planning and Management, Vol. 129, No.2, pp. 115-123.

Rajani, B. and Zhan, C. (1996), “On the Estimation of Frost Load.” Canadian Geotechnical Journal, 33(4), pp.629-641.

Royer, M.D. (2005). “White Paper on Improvement of Structural Integrity Monitoring for Drinking Water Mains.” US EPA report, EPA/600/R-05/038. http://www.epa.gov/ORD/NRMRL/pubs/600r05038/600r05038.pdf (20 June 2005)

Sacluti, F., Stanley S. J., and Zhang, Q. (1998). “Use of Artificial Neural Networks to Predict Water Distribution Pipe Breaks.” In Proceedings of the 15th Annual Conference of the Western Canadian Water and Wastewater Association, Calgary, AB, Canada.

Shamir, U. and Howard, C.D.D. (1979). “An Analytic Approach to Scheduling Pipe Replacement.” AWWA Journal, 71 (5), pp. 248-258.

Shehab Eldeen, T. (2001). "An Automated System for Detection, Classification and Rehabilitation of Defects in Sewer Pipes." Ph. D. Thesis. Submitted to the Department of Building, Civil, and Environmental Engineering, Concordia University, Canada.

Skipworth, P. Engelhardt, M. Cashman, A. Savic, D. Saul, A. Walters, G. (2002). "Whole Life Costing for Water Distribution Network Management." Thomas Telford Publishing, London, UK. ISBN 0727731661.

Stone, S., Dzuray, E. J., Meisegeier, D., Dahlborg, A. and Erickson, M. (2002). "Decision-Support Tools for Predicting the Performance of Water Distribution and Wastewater Collection Systems." US EPA, Project Report, EPA/600/R-02/029, http://www.epa.gov/ORD/NRMRL/pubs/600r02029/600R02029.pdf (30 September 2005)

UK Water Industry (1993). "Manual of Sewer Condition Classification." 3rd Edition, WRc, August 1993. ISBN 0902156896

Vanier, D.J. (2004). "Municipal Infrastructure Investment Planning (MIIP)." NRC Client Report, B-5123.4, part 1, 2004.

Walski, T.M., and Pellicia, A. (1982). "Economic analysis of water main breaks." Journal of AWWA, 74 (3), pp. 140-147.

Zayed, T. and Halpin, D. (2005). "Pile Construction Productivity Assessment." ASCE Journal of Construction Engineering and Management. Vol. 131, No. 6, June 1, pp.705-714.

Zhan, C., and Rajani, B. (1997). "On the Estimation of Frost Load in a Trench: Theory and Experiment." Canadian Geotechnical Journal. 34(4), pp. 568-579.

Zhang, Q. (2004). E mail. 11 February, 2005. qzhang@epcor.ca