Development of Wastewater Collection Network Asset Database, Deterioration Models and Management Framework

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

The dynamics around managing urban infrastructure are changing dramatically. Today's infrastructure management challenges – in the wake of shrinking coffers and stricter stakeholders' requirements – include finding better condition assessment tools and prediction models, and effective and intelligent use of hard-earn data to ensure the sustainability of urban infrastructure systems. Wastewater collection networks – an important and critical component of urban infrastructure – have been neglected, and as a result, municipalities in North America and other parts of the world have accrued significant liabilities and infrastructure deficits. To reduce cost of ownership, to cope with heighten accountability, and to provide reliable and sustainable service, these systems need to be managed in an effective and intelligent manner.

The overall objective of this research is to present a new strategic management framework and related tools to support multi-perspective maintenance, rehabilitation and replacement (M, R&R) planning for wastewater collection networks. The principal objectives of this research include:

(1) Developing a comprehensive wastewater collection network asset database consisting of high quality condition assessment data to support the work presented in this thesis, as well as, the future research in this area.

(2) Proposing a framework and related system to aggregate heterogeneous data from municipal wastewater collection networks to develop better understanding of their historical and future performance.

(3) Developing statistical models to understand the deterioration of wastewater pipelines.

(4) To investigate how strategic management principles and theories can be applied to effectively manage wastewater collection networks, and propose a new management framework and related system.

(5) Demonstrating the application of strategic management framework and economic principles along with the proposed deterioration model to develop long-term financial sustainability plans for wastewater collection networks.

A relational database application, WatBAMS (Waterloo Buried Asset Management System), consisting of high quality data from the City of Niagara Falls wastewater collection system is developed. The wastewater pipelines' inspections were completed using a relatively new Side Scanner and Evaluation Technology camera that has advantages over the traditional Closed Circuit Television cameras. Appropriate quality assurance and quality control procedures were developed and adopted to capture, store and analyze the condition assessment data. To aggregate heterogeneous data from municipal wastewater collection systems, a data integration framework based on data warehousing approach is proposed. A prototype application, BAMS (Buried Asset Management System), based on XML technologies and specifications shows implementation of the proposed framework. Using

wastewater pipelines condition assessment data from the City of Niagara Falls wastewater collection network, the limitations of ordinary and binary logistic regression methodologies for deterioration modeling of wastewater pipelines are demonstrated. Two new empirical models based on ordinal regression modeling technique are proposed. A new multi-perspective – that is, operational/technical, social/political, regulatory, and finance – strategic management framework based on modified balanced-scorecard model is developed. The proposed framework is based on the findings of the first Canadian National Asset Management workshop held in Hamilton, Ontario in 2007. The application of balanced-scorecard model along with additional management tools, such as strategy maps, dashboard reports and business intelligence applications, is presented using data from the City of Niagara Falls. Using economic principles and example management scenarios, application of Monte Carlo simulation technique along with the proposed deterioration model is presented to forecast financial requirements for long-term M, R&R plans for wastewater collection networks.

A myriad of asset management systems and frameworks were found for transportation infrastructure. However, to date few efforts have been concentrated on understanding the performance behaviour of wastewater collection systems, and developing effective and intelligent M, R&R strategies. Incomplete inventories, and scarcity and poor quality of existing datasets on wastewater collection systems were found to be critical and limiting issues in conducting research in this field. It was found that the existing deterioration models either violated model assumptions or assumptions could not be verified due to limited and questionable quality data. The degradation of Reinforced Concrete pipes was found to be

affected by *age*, whereas, for Vitrified Clay pipes, the degradation was not *age* dependent. The results of financial simulation model show that the City of Niagara Falls can save millions of dollars, in the long-term, by following a pro-active M, R&R strategy.

The work presented in this thesis provides an insight into how an effective and intelligent management system can be developed for wastewater collection networks. The proposed framework and related system will lead to the sustainability of wastewater collection networks and assist municipal public works departments to proactively manage their wastewater collection networks.

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Dedication

To my wife, Asima, and my parents, Azra and Younis, for their love and continued support.

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Chapter 1
Introduction

1.1 Background and Motivation

Wastewater collection system, an important and critical component of urban infrastructure, is responsible for safe and secure disposal of water from domestic, industrial, commercial, and public usage (Grigg, 2003). It is a common knowledge that most of wastewater collection infrastructure in many cities has either reached or near the end of its expected service life (Dalziel and Macey, 2004; Grigg, 2003). The concern about structural and operational performance of these systems is growing with increasing cases of pipelines collapses, flooding of streets and properties and groundwater contamination. Wirahadikusumah et al. (1998) wrote,

> "Defective sewer systems are 'time bombs', threatening to contaminate the groundwater and soil, in addition to causing traffic disruptions, loss of property, and in some cases, even loss of life."

According to Wirahadikusumah et al. (1999), thousands of kilometers of wastewater pipelines which were laid in different times over the history – some dating back to more than hundred years – remained virtually forgotten and untouched until a failure occurred. Iseley (2003) attributed this neglect to 'out of sight, out of mind' nature of these assets. Historically, there has been little to no investment to investigate their condition or to find the need for rehabilitation, and thus prolonging their lives. Now, there is a consensus amongst various agencies that billions of dollars of expenditures will be needed for the replacement of defective wastewater pipelines in the coming future if effective management strategies are not devised (Grigg, 2003; Mirza and Haider, 2003; S. Mirza, 2007; NTREE, 1996; Wirahadikusumah et al., 1999). Failure to do so risks the public health, and economic and environmental gains of the past decades.

The public works departments and related agencies at municipalities are also under pressure from governments and regulators at all levels – federal, provincial, and local – to document current condition of their wastewater systems, and come up with viable plans for their sustainability in the future. For example, in Ontario, the proposed *Bill 175: Sustainable Water and Sewage Systems Act, 2002*, makes it mandatory for municipalities to assess costs to operate, maintain, and replace water and sewerage systems, and devise full-cost recovery plans (Ministry of the Environment, 2002). In particular, it requires municipalities to prepare a report, including inventory and management plans, for sustainable water and wastewater infrastructure. This is a tremendous challenge for infrastructure managers who are expected to develop wastewater collection systems' capital improvement plans with little information about current condition of their infrastructure and how it will deteriorate in the future.

According to Dalziel and Macey (2004), "the basic requirements for an asset management system are that, it must: (1) maintain an inventory of assets; (2) manage asset condition data; and (3) provide annual estimates of costs required to maintain an asset's condition at or above the target condition level." Most of the Canadian municipalities lack inventory data, and do not have detailed description and history of condition of various infrastructure facilities (Mirza and Haider, 2003). In 2003, a study on current asset management practices for municipal water and wastewater systems revealed that about 52% of the surveyed utilities in Ontario, Canada, do not have an asset management plan, and therefore, will not be able to implement the requirements of the Ministry of the Environment Bill 175 (PricewaterhouseCoopers, 2003). A similar survey in the United States reported by Malik et al. (as cited in Wirahadikusumah et al., 1999) revealed that most of the responding cities did not maintain historic data on the condition of wastewater collection networks. Therefore, the efforts to develop a comprehensive asset management framework – that allows utility managers to effectively estimate future investment costs and timings of applications – are seriously impeded by non-existent or incomplete datasets of questionable quality.

Sewer system rehabilitation programs involve immediate decisions (such as, identification of rehabilitation actions that are already overdue), and a planned sequence of future rehabilitation decisions. Present condition assessments provide a basis for the former, but the later requires forecasting models on future infrastructure condition (Baur and Hertz, 2002; Kleiner, 2001). Wirahadikusumah et al. (2001) and Wirahadikusumah and Abraham (2003) discussed the challenging issues (e.g., lack of quality data) in developing better deterioration models for wastewater pipelines. Literature review also revealed some deterioration models proposed on mere assumptions and expert opinions. For example, Kathula et al. (1999) and Stevenson and Macey (2005) applied expert opinion about the degradation of wastewater systems, and developed imaginary deterioration curves. The pure subjective approaches ultimately render to guess work, and raise serious questions about correctness, credibility and validity of suggested models and maintenance management plans based on them.

1.2 Research Objectives and Scope

The overall objective of this research is to provide a framework for intelligent and cost-effective maintenance, rehabilitation and reconstruction (M,R&R) of wastewater collection systems. To achieve this goal, specific objectives include the following:

1. Investigate historic perspective and review state-of-the-art with regards to condition assessment and rehabilitation planning of wastewater collection systems;

2. Develop a high quality wastewater collection network asset database, and devise a framework and related prototype system to combine wastewater infrastructure data from heterogeneous organizations;

3. Investigate state-of-the-art deterioration models for wastewater collection pipelines and develop new model(s).

4. Explore strategic planning theories and management principles to develop a multi-perspective (e.g., financial, operational/technical, regulatory, socio/political) management framework applicable to wastewater collection systems, and demonstrate applicability of the proposed management framework using a case study.

5. Demonstrate application of the proposed framework and deterioration model(s) for strategic financial planning of wastewater collection networks.

1.3 Thesis Organization

The thesis sequentially addresses the research objectives in an integrated-article format – that is, each chapter is in the form of a paper already submitted (or to be submitted) to a technical journal or refereed conference.

Chapter 2 provides a historic perspective with respect to wastewater collection systems and reviews state-of-the-art in wastewater pipelines condition assessment and rehabilitation planning. It also highlights the need for better condition assessment technologies and improved understanding of deterioration of wastewater pipelines.

Chapter 3 discusses the development of a public-private partnership and research collaboration to achieve the objectives outlined in Section 1.2. It also presents the development of a wastewater collection network asset database, and provides a framework and support system to integrate heterogeneous data from multiple wastewater collection systems.

Chapters 4, 5 and 6 are related to the deterioration modeling of wastewater pipelines. In Chapter 4, ordinary and binary logistic regression techniques are applied to wastewater pipelines condition assessment data collected by the author from the City of Niagara Falls, and some of their limitations are discussed. Chapter 5 presents an ordinal regression model based on cumulative logits, and Chapter 6 discusses the continuation-ratio model to model the degradation behaviour of wastewater pipelines.

Chapter 7 reviews the existing civil infrastructure management frameworks/systems, and proposes a new multi-perspective management framework. A case study is also presented to demonstrate the implementation of the proposed framework.

Chapter 8 and 9 present the integration of management framework, economic principles and deterioration modeling for strategic financial planning of wastewater collection systems.

Conclusions and recommendations for future work are discussed in Chapter 10.

The work presented in this thesis will: (1) help municipal public works departments (PWD) to develop integrated management strategies for intelligent and cost-effective maintenance, rehabilitation and replacement (M,R&R) of wastewater pipelines; (2) persuade decision-makers to provide financial support for wastewater collection systems' M,R&R programs; (3) help PWD in developing short-term operational and long-term capital improvement plans; (4) protect public health and environment; and (5) increase stakeholders' confidence.

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Chapter 2

Wastewater Collection Systems and Advances in Pipeline Asset Management Using Digital Side Scanning Evaluation Technology

2.1 Abstract

This paper provides an overview of wastewater collection systems and describes the history of pipelines inspection technology used for condition assessment of wastewater and storm water networks. It then describes recent advances in digital side scanning evaluation camera technology and its advantages for network asset management. Challenges facing municipal network managers and operators are also discussed. It is argued that pipe scanning technology: (1) can reduce network inspection and renovations costs; (2) can be used to determine pipeline deterioration rates; and (3) is preferred for the development of sustainable network asset management plans.

2.2 Wastewater Infrastructure Systems

Wastewater or sewage is the water disposed of after usage. *Wastewater collection system* also known as *sewerage system* consists of pipes that come together at manholes. It collects, transmits, and disposes of sewage from domestic, industrial, commercial, and public users. According to Grigg (2003), most of the wastewater or sanitary sewage is of municipal origin, and mainly consists of domestic and commercial wastewater.

The major components of a sewerage system include collection system consisting of pipelines, manholes, lift stations, interceptor sewers, wastewater treatment plants, and outfall sewers as shown in Figure 2.1.

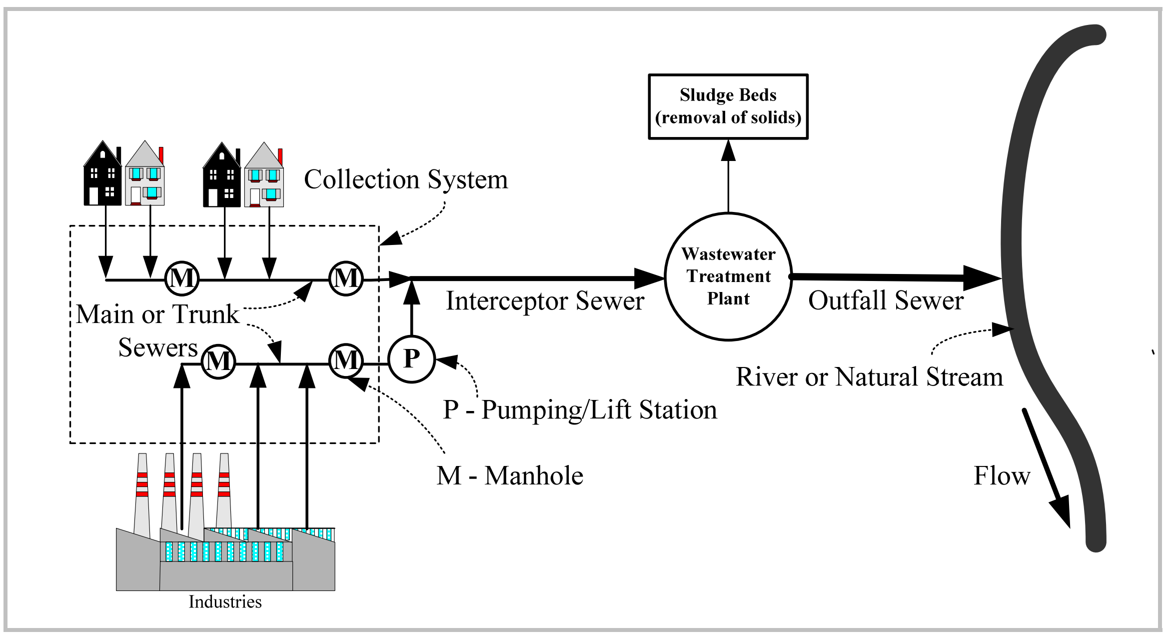

Figure 2.1: Wastewater Infrastructure System (adapted from Grigg, 2003)

2.2.1 Types of Wastewater Pipelines

Wastewater pipelines may be classified according to flow types (e.g., gravity or forced mains), nature of flow, and material and geometry. Common classification of gravity sewers is discussed below.

1. Nature of Flow

There are usually two types of wastewater systems in any typical municipality:

a. **Separate Systems:** Separate pipelines for storm water and sanitary wastewater.

   Sanitary Sewers: Sewers that transport sanitary or industrial sewage only.

   Storm Water Sewers: Sewers that dispose of storm water.

b. **Combined Systems:** Sewers that transport wastewater from sanitary and storm drainage mixed together. Most of the early systems are combined systems as 'dilution was the solution', instead of treating wastewater.

2. Material and Geometry

Wastewater pipelines are broadly classified as rigid or flexible**.** *Rigid sewers,* such as concrete and vitrified clay pipes, are designed to withstand vertical loads on their own, and usually do not need surrounding soil support. *Flexible pipes,* such as Polyvinyl Chloride (PVC) or Polyethylene (PE), need side support to sustain loadings or else they will buckle and/or deform under load. Brick, vitrified clay and concrete rigid pipes sewers are rigid, but behave like flexible when they lose mortar and side support.

Figure 2.2 shows common materials used in wastewater collection networks. They include Reinforced Concrete (RC), Vitrified Clay (VC), bricks, Polyvinyl Chloride (PVC) and Polyethylene (PE). Sewers are round (mostly in RC, VC, PVC and PE pipes), square, oval, rectangle and egg shaped (usually in brick sewers).

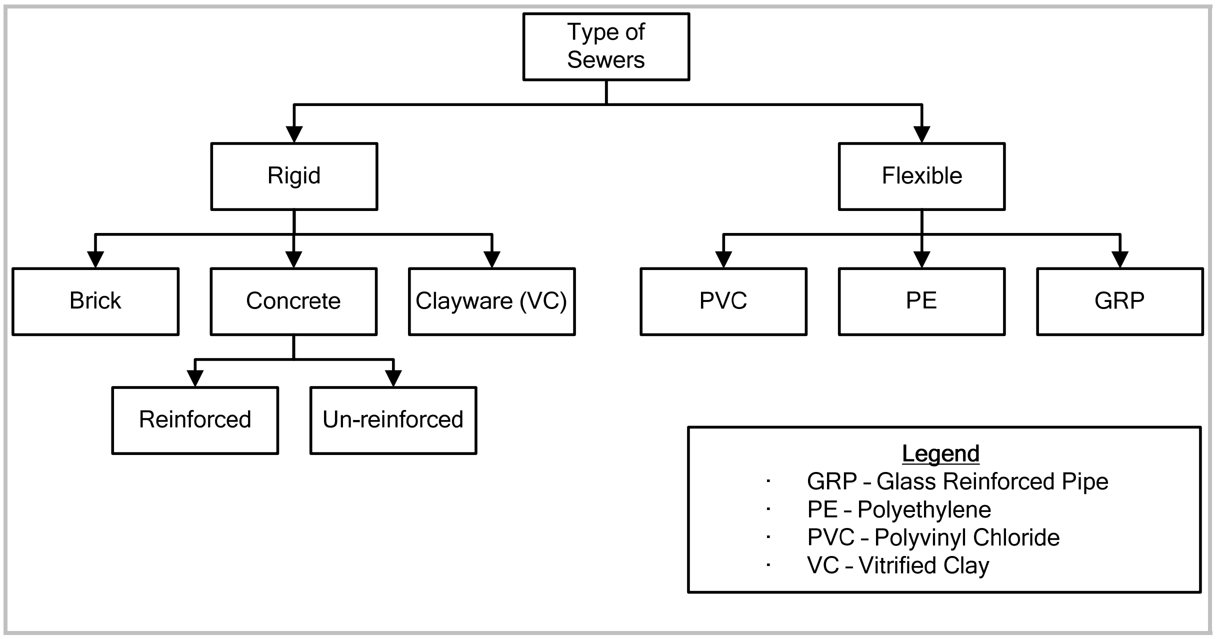

Figure 2.2: Types of Sewers Based on Material

2.3 Wastewater Pipelines Inspection

Over the past decade significant technology advancements has taken place in the wastewater pipelines inspection industry. In the late 1800's and early 1900's, wastewater pipeline inspection consisted of pulling or floating a candle through a sewer. It was thought that water infiltration would extinguish the candle as it moved through a sewer. Thus, if a candle emerged from a downstream manhole in lit condition, the pipe section was considered to be in good condition. In the mid 1960's, the first closed circuit television (CCTV) systems were developed by a contractor, and sold commercially for the inspection of buried pipelines. These early systems used the RCA Vidicon and Newvidcon image tube that was commercially produced in the early 1950's. The Vidicon image tube was a major technology breakthrough as it allowed for the development of a 125mm (5 inch) camera that could be pulled through a 200mm (8 inch) or larger pipeline (Bennett and Corkhill, 2006). In 1964, the contractor started a separate CCTV equipment business. These early camera systems produced black and white images with 325 lines of resolution and required 10 lux or more of light to produce a picture. A lux is equivalent to one candle directed one meter towards the pick-up device. Since the development of the first CCTV camera systems, many technological advancements were implemented – such as, tractor and cable management systems, lighting, lines of resolution, color video, pan and tilt capabilities, computerized video imaging, and the development of imaging processing and inspection software – to improve equipment operation efficiency and image quality.

In 1994, the TOA Grout and CORE Corporation, and the Tokyo Metropolitan Government's Sewer Service (TGS) Company developed Sewer Scanner Evaluation Technology (SSET) camera in Japan (Abraham and Chae, 2002). SSET technology consists of a 360 degree fisheye digital scanner with mechanical inclinometer and gyroscope. The technology differs from CCTV in that it produces a digital side scan of pipe wall along with the traditional CCTV forward looking video. The digital scanner scans the pipe wall millimeter after millimeter to produce a continuous, open unfolded side scans of pipe (Iseley, 2002). The image is a composite of a series of images which are joined via a software interface (see Figure 2.3).

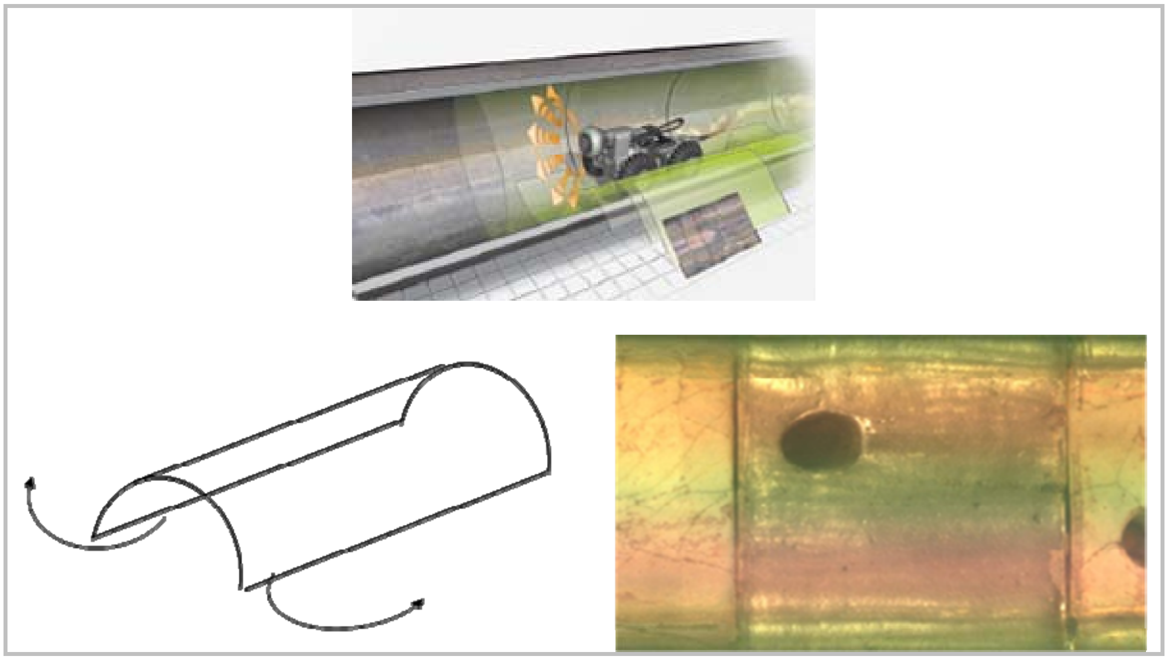

Figure 2.3: Sewer Scanner Evaluation Technology Pipe Scan and Unfolded Pipe Image (courtesy of Envirosight LLC.)

The unfolded pipe image permits computer-aided measurement of the position and size of objects, and an overview image gallery of the inspected pipe (Abraham and Chae, 2002; Iseley, 2002). The traditional CCTV front view images are also captured. Online location data is collected using an inclinometer that measures and records vertical movement, and a gyroscope that measures and records horizontal movements. The distance from starting point is determined from a power cable. Blackhawk-PAS Inc. commercialized the third generation SSET camera system in North America in 2001. In 2007, Envirosight LLC. introduced iPEK's DigiSewer® camera system – the fourth generation of SSET – to the North American market (see Figure 2.4). The DigiSewer® camera system has the ability to scan pipes from 150 to 800mm (6 to 32 inches) using LED lights.

Figure 2.4: iPek DigiSewer® Camera System Distributed by Envirosight LLC.

In 1999, IBAK in Germany started the development of a new kind of optical sewer inspection technology called PANORAMO 3D Optical Scanner. IBAK's main objective was to develop a new camera system that overcomes the functional limitations inherent in existing CCTV systems (Werner, 2002). In 2002, IBAK introduced the PANORAMO camera system at the No-Dig Show in Copenhagen. This camera system uses two high resolution digital photo cameras with 185° wide-angle lenses, integrated into the front and rear section of the housing (Werner, 2002). During pipe inspections, parallel-mounted xenon flashlights are triggered at the same position in the pipe. Hemispherical pictures are put together to form 360° spherical images using proprietary software (see Figure 2.5).

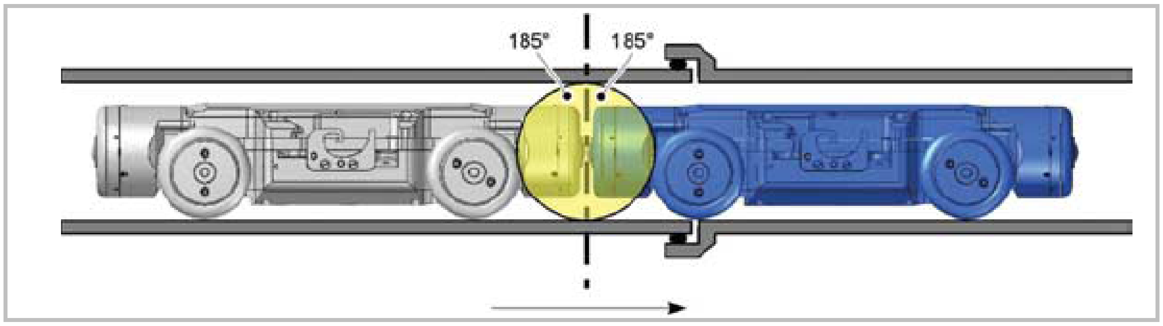

Figure 2.5: PANORAMO Camera (at two different positions in a pipe. Pictures are joined together to form a 360 degree image)

An unfolded view of the inner pipe surface can also be produced in a format similar to the DigiSewer® camera system. In 2007, RapidView LLC. introduced the PANORAMO camera system to North America for the inspection of 200mm (8 inch) and larger pipelines (see Figure 2.6).

Figure 2.6: IBAK PANORAMO Camera System Distributed by RapidView LLC. in North America

2.4 Pipeline Defect Coding

As the use of CCTV cameras for inspection of wastewater pipelines increased so did the need for a uniform and standard pipeline defect coding system. The following section details the evolution of current defect coding standards used in North America.

CCTV pipeline inspections are completed by an operator as he remotely drives the camera down a pipe. As the camera advances, the operator codes all observed pipeline structural and operational defects using a defect condition coding system. In North America, two wastewater pipeline defect condition classification systems are predominantly used. They include: (1) Manual of Sewer Condition Classification (MSCC) third edition, developed by the Water Research Center (WRc) in the United Kingdom (UK); and (2) Pipeline Assessment and Certification Program (PACP), developed by National Association of Sewer Service Companies (NASSCO) with the help of WRc.

The MSCC was first published in 1980 to provide a national standard defect coding system for this type of survey work in the UK. In 1994, WRc published the third edition of MSCC. The unique feature of the MSCC third edition is that it updates the rules to increase consistency of data entry to assist those involved in collection, validation, and storage of data on a computer (WRc, 1993). In 2004, the fourth edition of MSCC was published. The fourth edition contains new codes and guidance on the use of the coding system for condition inspection of manholes and inspection chambers (WRc, 2004). In 1994, the Association of Pipeline Inspectors of Ontario (APIO) adopted WRc's MSCC third edition as the standard defect coding system in Ontario, Canada. APIO also developed a CCTV operator certification program. In 1998, APIO changed its name to the North American Association of Pipeline Inspectors (NAAPI) as municipal pipeline inspection contracts in Canada began to specify certified APIO CCTV operators. To ensure that CCTV operators maintained a high level of coding accuracy and proficiency, NAAPI implemented a Reviewer's course for engineers and technicians who review and use CCTV inspection data, and a one day CCTV operators' re-certification course. The operators' one day refresher course is designed to ensure that NAAPI certified operators maintain a high level of consistent defect coding. For an operator to be NAAPI certified, passing grades of 80 and 85 percent are required on the certification test and re-certification examination, respectively.

In 2002, NASSCO published PACP, to meet the wastewater pipeline inspection needs for the United States (NASSCO, 2006). The WRc was retained by NASSCO to develop PACP. In 2004, WRc appointed NASSCO, USA, as its exclusive licensee in North America to market, distribute, and sell WRc's manuals of Sewer Condition Classification, and to provide training in its use and application.

2.5 Pipeline Condition Rating

The Sewerage Rehabilitation Manual (SRM), also published by WRc (WRc, 2001; WRc, 2004), describes a wastewater pipelines renovation decision making process that has been adopted in the United Kingdom and Canada. The first edition of the SRM was published in 1986, and the current fourth edition was published in 2001. The SRM determines the structural and operational performance of wastewater pipelines by assigning scores to MSCC third edition defects based on their type and severity. These scores are transformed to structural and operational Internal Condition Grades (ICG) of 1 to 5, with 1 being the best or acceptable condition and 5 being the worst or collapsed state (WRc, 2001). Based on supplementary information, such as soil type and surcharging frequency, the structural ICG are modified to Structural Performance Grades (SPG). It should be noted that the SRM fourth edition was developed for use with MSCC third edition codes. Currently, no SRM condition grading methodology exists for the MSCC fourth edition codes, or NASSCO's PACP codes. The general principles of the SRM also formed the basis for the European Standard EN752-5: Drain and Sewer Systems Outside Buildings: Part 5 Rehabilitation. Since the United Kingdom and Canada have had outstanding success with the implementation of the SRM ICG methodology, the SRM process can be considered to be an acceptable and good approach for determining pipeline current condition states.

NASSCO's PACP manual contains a pipeline condition rating scheme that varies from 1 to 5. The PACP condition rating depends on average score (total defects score for a manhole to manhole pipe segment divided by the number of defects) rather than peak score as used by the WRc. Unlike WRc's SRM, the PACP manual has no detailed decision making process. Presently, limited published data exists to validate the PACP defect scores rating system in North America. According to Stantec (2009), usage of average scores instead of peak scores for condition rating is a limitation of PACP methodology. PACP protocol, therefore, may not be able to accurately prioritize rehabilitation needs of wastewater collection systems (Stantec, 2009).

2.6 Wastewater Pipeline Construction and Pipeline Inspection

In North America, wastewater distribution network construction commenced in urban centers in the late 1880's to reduce the risk of health related diseases transmitted through human wastes. Thus, wastewater networks were constructed to reduce health related issues. As the population of urban core expanded during the 1900's to the 1950, the construction of wastewater networks also expanded. Prior to the development of CCTV cameras, pipeline condition assessments were typically performed to determine locations of significant infiltration and to investigate problematic areas.

In the 1960's, urban development moved from urban core to the development of suburbs. This was also a period of high urban population growth and wastewater network construction as people moved from city centers to suburbs. During this time period, the need to protect environment also became a significant political and social issue. Therefore, wastewater networks were required to protect environment and public health. In the 1980's, municipalities started to deal with fiscal responsibility issues created by an increased need to network renovation due to pipe segments reaching their design life of 50 to 75 years, and network operators' limited and scarce financial resources. In the late 1990's and early 2000's, government fiscal downloading, and new legislative and regulatory requirements (e.g., the Governmental Accounting Standards Board (GASB) Statement 34 in the United States, and the Canadian Institute of Chartered Accountants' Public Sector Accounting Board (PSAB) statement PS3150 in Canada) began to force all wastewater networks operators to show that they are fiscally accountable.

With the development of CCTV cameras in the 1960's, initial pipeline inspections surveys were expensive. Thus, initial pipeline surveys were typically only performed on projects where the consequences for pipeline failures were high, such as the inspection of power plants water intake and discharge lines, or to investigate municipalities' wastewater collection pipelines problems. In the 1970's, the demand to complete CCTV surveys increased, and the cost to carry out those surveys decreased. By the late 1980's and early 1990's, many municipalities began to embark on CCTV condition assessment programs to determine pipeline segments' current condition states so that they could move from a reactive asset management strategy – fix it when it breaks – to a more proactive asset management approach – that is, use limited financial resources on the right asset at the right time. To become proactive, utility owners/managers needed to know the present condition state for critical pipeline segments. The mandate for utilities' fiscal responsibility and accountability also increased the need for high quality pipeline inspection surveys. To demonstrate fiscal accountability, network revenue must meet or exceed present and future predicted operation, maintenance, construction, renovation, and renewal expenses. To determine network asset valuation along with present and future revenue needs, the utility owners are now required to know pipelines' current and expected future (e.g., 5, 10, 15, and 50 years) condition states.

Current guidelines, with limited or no asset deterioration knowledge, suggest that the useful life for wastewater pipelines range from 40 to 75 years (see for e.g., Ministry of the Environment, 2007; NAMS, 2002). The absence of asset deterioration knowledge necessitates the Canadian municipalities to make many unsubstantiated assumptions about the timing and volume of capital expenditures so that they can comply with PSAB and other government and regulatory requirements. These unsubstantiated assumptions will most likely result in an under or over-estimation of assets future operational and capital needs. To determine realistic life-cycle asset operation and maintenance costs, it is imperative that assets' deterioration behavior is well understood.

2.7 Wastewater Network Deterioration Modeling

Commonly used regression based statistical techniques for modeling the deterioration of wastewater pipelines include: expected value methodology (ordinary linear or non-linear regression), binary/dichotomous logistic regression, and ordered probit regression based on latent variable formulation. Other statistical techniques, such as Markov chains, and Bayesian and reliability based methodologies have also been applied to CCTV inspection datasets. The majority of the existing inspection datasets were developed by uncertified CCTV operators with little to no data quality control and quality assurance protocols. Using the City of Niagara Falls SSET inspection survey database, developed at the University of Waterloo using quality assurance and quality control protocols, it has been found that ordinary regression based deterioration models for wastewater networks violated model assumptions (Younis and Knight, 2008). The deterioration models based on ordered probit regression were found to be overly complex in terms of the number of parameters to be estimated, and therefore, made the interpretation of results quite challenging. The deterioration models, developed using binary logistic regression, divided the data into pass or fail categories while ignoring the rank order information in the data. Further research is required with respect to *age* and *material* interaction, and other factors that influence the degradation behavior of wastewater pipelines, e.g., environment, soil and groundwater chemistry, physical and chemical characteristics of wastewater, and static and dynamic loading. To develop realistic waster pipeline deterioration models, it is imperative that quality (not quantity) pipeline inspection datasets are developed.

2.8 Need for A Wastewater Pipeline Inspection Approach

The use of CCTV inspection surveys defect coding and WRc's pipeline Internal Condition Grades (ICG) is an excellent methodology for determining the current condition of a pipeline and developing network renovation work programs. However, the use of CCTV inspection surveys and ICG for the determination and measurement of network deterioration rate has had limited success for the following reasons.

Firstly, the authors are aware of a UK pipeline segment, inspected by WRc, improved in condition (ICG 3 to ICG 2) after 15 years of service with no renovation or renewal. An explanation provided for how this physically impossible improvement can take place is that the initial CCTV operator coded the pipeline with defects that were assigned higher defect scores due to the initial poor quality camera image. This example highlights the subjective nature of using pipeline defect coding to determine a pipeline's ICG, even when a well-trained and a certified camera operator is used. It also highlights the challenge of using ICG for pipeline deterioration modeling.

Secondly, many municipalities in North America have limited high quality CCTV inspection data that can be used to determine network deterioration rates. The Ministry of Finance in Ontario, Canada, completed a survey (PricewaterhouseCoopers, 2003) to investigate municipal water and wastewater systems asset management practices. This survey found that among the responding Ontario municipalities, 17% do not perform inspections for condition assessment, and of those who do perform inspections, 33% do not record the results of the inspections. The good news is that since the mid 1990's most Canadian municipal CCTV inspection contracts state that all CCTV surveys are to be completed and coded by a NAAPI certified CCTV operators. Since APIO/NAAPI inception, CCTV operators' course instructors were carefully selected and trained to ensure that all course offerings are provided using experienced CCTV operators with no conflict of interest and a high level of consistent instructions. This training model, along with CCTV operators' re-certification every three years, ensures that high quality CCTV inspection surveys and defect coding are completed in Canada. Due to the lack of operator certification in the USA prior to NASSCO's PACP in 2001, pipeline inspection surveys in the USA are often of questionable quality, and lack defect coding consistency. NASSCO's launch of PACP certification in the USA has made a significant improvement in operators' defect coding consistency. However, NASSCO's PACP presently suffers with the following issues: (1) NASSCO's PACP training is not provided to the same standard as NAAPI's training i.e., no conflict of interest policy, no requirement for course instructors to meet field experience criteria prior to becoming an instructor, lack of consistent instructor training, and no operator re-certification requirement; and (2) no standardized methodology exists for the determination of pipelines' internal condition grades using PACP defect codes. This is a critical issue for pipelines deterioration modeling and networks' asset management.

WRc's Internal Condition Grades (ICG) were developed as distinct/discrete condition grades as shown in Figure 2.7. Thus, a pipeline remains in a condition grade until a point in time when it meets the requirement to move into the next condition grade. For example, the pipeline in Figure 2.7 remains in ICG 1 from installation to 21 years, and at age 21.1 years it jumps immediately into ICG 2.

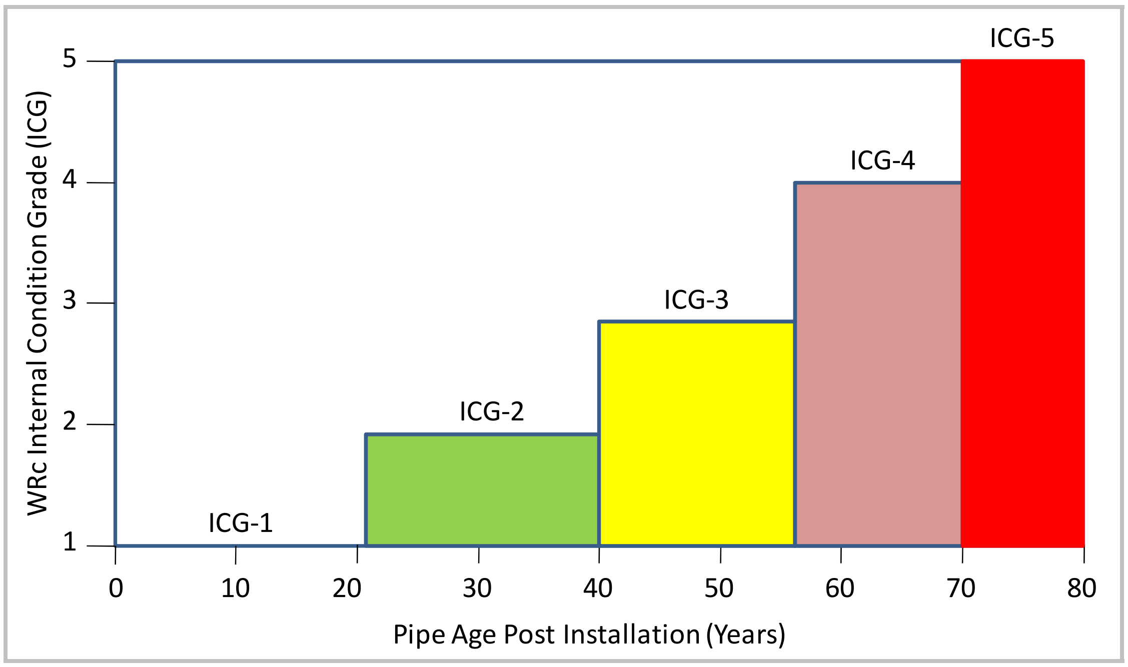

Figure 2.7: Conceptual Pipeline Deterioration Plot Using WRc's ICG Methodology

In the field, pipeline deterioration function may take a linear or non-linear form similar to that shown hypothetically in Figure 2.8. The shape of deterioration curve (i.e., linear or non-liner) will be controlled by pipelines' deterioration process that occurs in a pipe segment. For example, if it is determined that deterioration is due to corrosion that occurs at a constant annual rate (such as H_2S attack), the deterioration curve will be linear. If the pipeline deterioration process is due to groundwater fluctuations and soil infiltration, the deterioration curve may take a non-linear form.

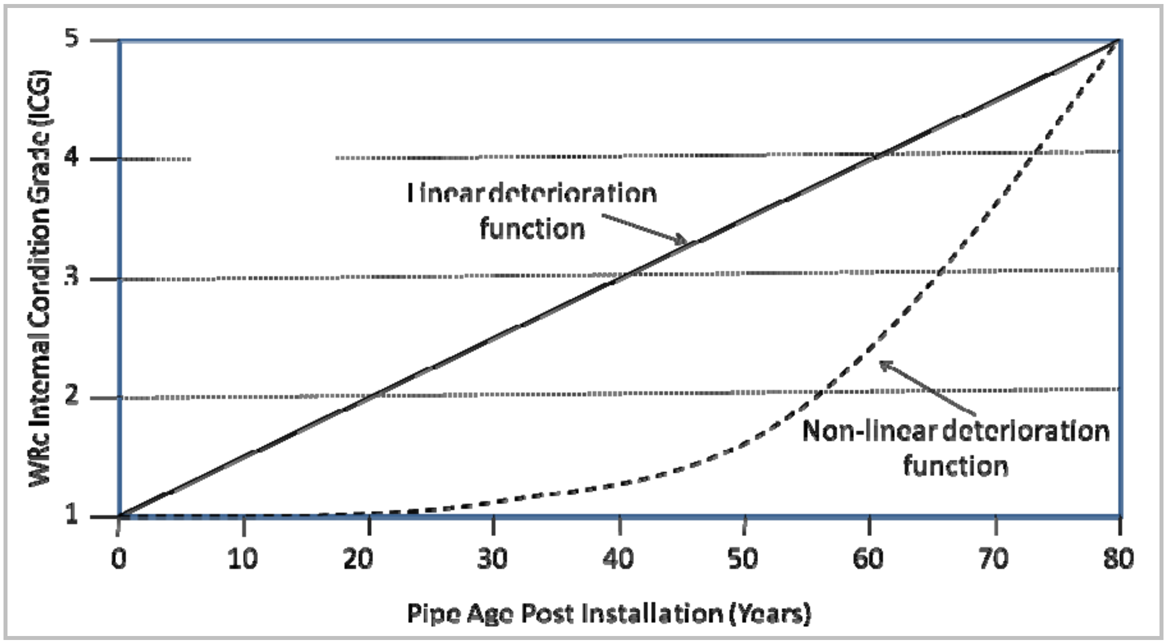

Figure 2.8: Conceptual Pipeline Segment Deterioration Curves – Linear - Linear and Non-Linear

Pipeline asset management can be described as fixing the right assets at the right time. For this purpose network operators must know where they are on the deterioration curve. If the costs to renovate a pipeline in ICG 5, 4, 3, and 2 are \$1000, \$750, \$500, and \$250 per meter, respectively, it is imperative to be able to predict when a pipeline segment will enter into a particular ICG. For example, Figure 2.9 shows that a pipeline segment will enter ICG 3 in approximately 40 years if the deterioration function is linear and in 67 years if the deterioration function is non-linear.

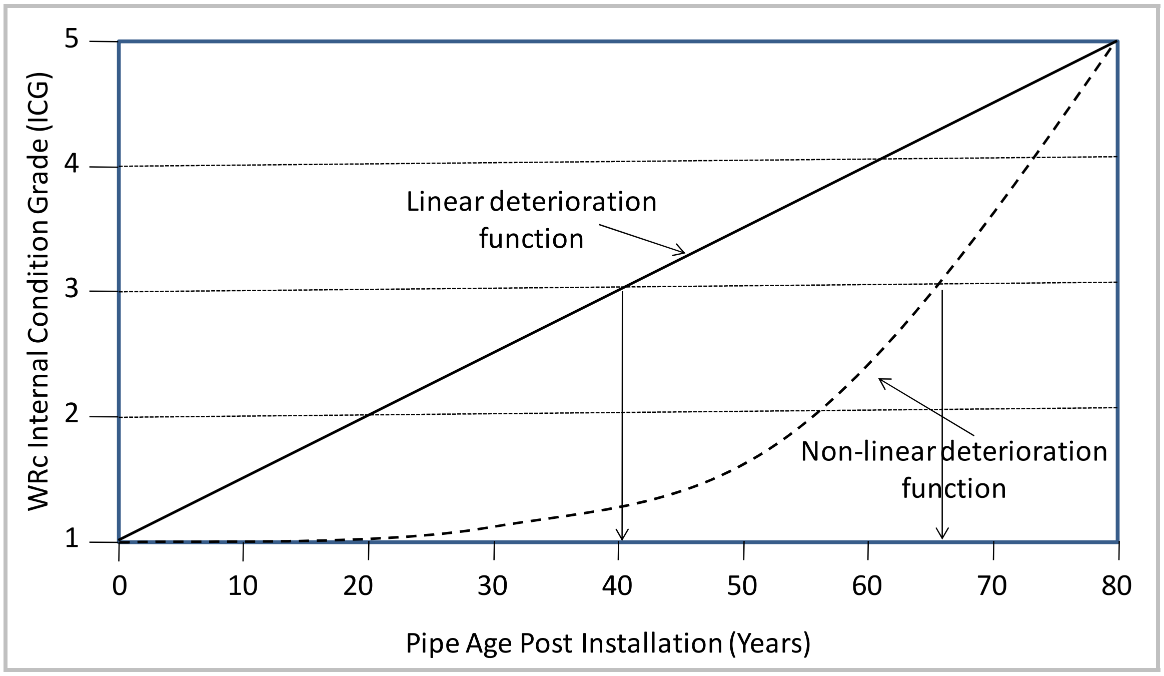

Figure 2.9: Pipe Age at ICG 3

2.9 Advantages of Moving To the New Scanning Technology for Wastewater Pipelines Asset Management

DigiSewer® and PANORAMO wastewater pipelines inspection systems offer many advantages over traditional CCTV camera systems. The main advantage of these new systems – in terms of wastewater network asset management – is the ability to accurately measure pipelines' defects changes between successive inspections. This unique feature allows utility owners, for the first time, to accurately measure changes in defects over time when an initial survey is used as a baseline reference survey. These new camera systems also eliminate the need for operators to pan and tilt, and for defect coding to be completed by the operator during pipe scanning. These advantages allow for the implementation of defect coding quality control and quality assurance programs that will allow for the development of high quality databases to be used for network deterioration modeling. To develop high quality defect and pipe condition rating databases, it is imperative that all inspection camera operators and defect coders are highly trained and certified by an independent third party organization. This organization must use experienced trainers and have protocols in place to ensure certified individuals meet or exceed stringent knowledge requirements. Failure to maintain this standard will compromise the quality of inspection data, and its use and value in the development of effective asset management practices. Utility owners must also implement quality assurance and quality control programs to check that all defect coding is of high quality prior to uploading it into an asset management database program.

2.10 Conclusions

Wastewater utility operators' mandate has evolved over the past few decades to include public health, protection of the environment, fiscal responsibility, and financial accountability. These changes along with the development of wastewater inspection technologies have increased the need for utility owners to complete inspection surveys. Aging wastewater networks and new government mandated planning and fiscal reporting requirements have changed utility owners information needs from understanding networks' present condition state to prediction of networks' condition state into the future (e.g., 5,10, 25, 50, 75 and 100 years). To complete the later task, utility operators and/or network asset management groups need realistic wastewater deterioration models. A review of the literature and analysis of current methods to determine wastewater deterioration rates has found that these models are of limited use as they were developed using CCTV defect and pipe rating datasets of questionable quality. If realistic deterioration models are to be developed, utility owners must commence with the development of new high quality inspection databases, and ought to share data beyond organizational confines. The new side scanning camera equipment (DigiSewer® and PANORAMO) may be the inspection technology of choice as it has many significant advantages over traditional CCTV camera equipment for the development and validation of pipeline deterioration models.

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Chapter 3

Development of Wastewater Collection Network Asset Database and Data Integration Framework

3.1 Abstract

Two major issues related to understanding the performance and effective management of wastewater collection systems include: (1) lack of good quality inventory and condition assessment data; and (2) lack of conception to extract useful information from imminent proliferation of heterogeneous data from multiple sources and formats at various municipalities. To obtain high quality condition assessment data (and to develop a database application) on wastewater collection systems, a collaborative research initiative was undertaken in 2005 with the Public Works Department at the City of Niagara Falls, PipeFlo Contracting Corp., and the Centre for Advancement of Trenchless Technologies (CATT) located at the University of Waterloo. Additionally, a framework and related system to integrate heterogeneous data from various municipalities is proposed.

This paper presents: (1) a case study that discusses why and how the City of Niagara Falls entered into a public-private partnership, with the help of CATT, to bring state-of-the-art Sewer Scanning and Evaluation Technology (SSET) to the City (and Canada); (2) the development of WatBAMS (Waterloo Buried Asset Management System) – a high quality wastewater pipelines condition assessment database; and (3) the development of a framework and related system, BAMS (Buried Asset Management System), to integrate heterogeneous data using XML (eXtensible Markup Language) specifications and technologies. Project challenges and useful lessons learned from building such a collaborative research partnership are also discussed.

This undertaking will advance the buried asset management science by providing: (1) high quality condition assessment data on wastewater pipelines for current and future research; and (2) a conceptual framework and prototype to facilitate the integration of data from a spectrum of sources (organizations and systems) to create new knowledge and test the existing one.

3.2 Introduction

Buried infrastructure – that includes wastewater pipelines in addition to water and other utility lines – are the most important and critical yet the most ignored amongst the entire civil infrastructure systems. In case of pavements and bridges, significant research work has been carried out under various initiatives. For example, in 1987, US Department of Transportation undertook Long-Term Pavement Performance (LTPP) program – a comprehensive 20-year research initiative worth US $50 million to monitor and study in-service pavements (U.S. Department of Transportation, 2009b). US National Bridge Inspection Program (U.S. Department of Transportation, 2009a), commenced in 1968, maintains inventory and condition assessment data in a National Bridge Inventory System. Contrarily, scarcity and poor quality of the existing data on wastewater pipelines are well-known issues (see for e.g., Baik et al., 2006; Davies et al., 2001; Mirza, 2007; PricewaterhouseCoopers, 2003; Watt et al., 2006; Wirahadikusumah et al., 2001; Wirahadikusumah and Abraham, 2003), and therefore, limited research related to in-service performance of wastewater collection systems has been carried out. The majority of the existing wastewater collection pipelines' condition assessment data collected using the traditional Closed Circuit Television (CCTV) cameras are (Iseley, 1999; Wirahadikusumah et al., 1998): (1) *very* subjective – that is, data depend upon the judgment of operators responsible for inspecting and recording defects in the field; and (2) time consuming and cumbersome to review. Furthermore, the CCTV inspections are non-reproducible – therefore, unsuitable to estimate deterioration rates – and the process is inefficient as the operator has to stop and record defects at each defect location during inspection process (Chae et al., 2003; Iseley, 1999; Wirahadikusumah et al., 1998).

Compared to other data-intensive disciplines, such as bioinformatics, and life, medical and social sciences – where technical advancements in data collection, storage, transfer, and analysis have revolutionized the way data is utilized – data management and utilization in buried infrastructure management is still in its infancy. Figure 3.1 shows the number of published and web-accessible molecular biology databases available to researchers and decision-makers. Baker and Cheung (2007) pointed out that the numbers presented in Figure 3.1 represent only a fraction of biological databases that actually exist. Due to the lack of adequate data on wastewater collection systems, municipalities and researchers often resort to make unsubstantiated assumptions regarding life-cycle performance of these systems. For example, regardless of pipe material, many existing guidelines and *best* management practices advocate using a service life varying from 40 to over 70 years for wastewater pipelines (see for e.g., Hudson et al., 1997; NAMS, 2002; and OMBI, 2007). Contrarily, the research shows that the degradation trends differ depending upon the pipe material (Baik et al., 2006; Micevski et al., 2002; and Younis and Knight, 2010). Another example is the Markov chains based deterioration models for wastewater pipelines (see for e.g., Baik et al., 2006; Micevski et al., 2002; Wirahadikusumah et al., 2001; and Wirahadikusumah and Abraham, 2003) where it is not possible to verify the assumptions of stationarity and homogeneity of Markov chains due to limited data (Wirahadikusumah et al., 2001).

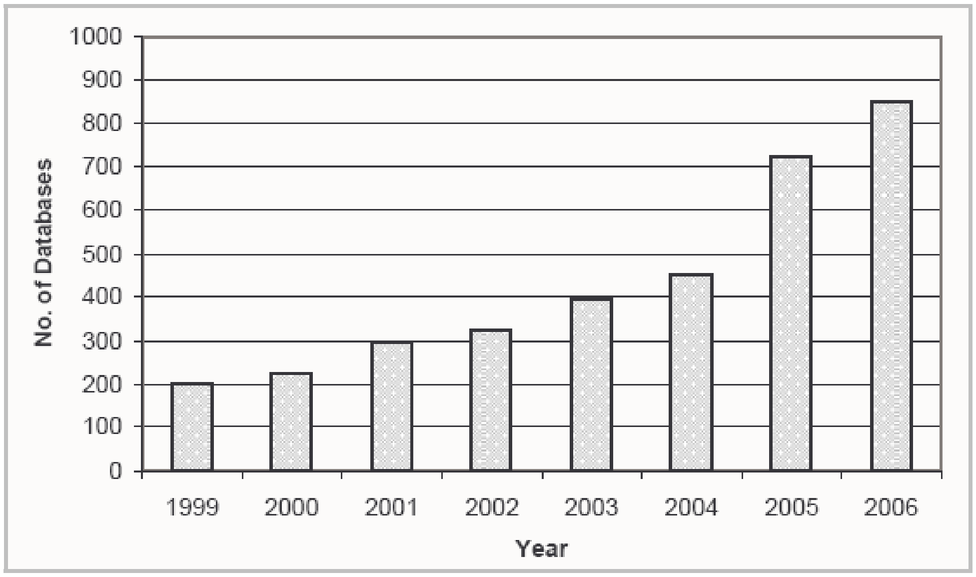


Figure 3.1: Number of databases published in the Nucleic Acids Research (NAR) Database Issues (Baker and Cheung, 2007)

The recent upsurge in urban infrastructure inventory and condition assessment data collection – resulting from governmental and regulatory requirements, such as Ontario Ministry of Environment *Regulation 453/07* made under the *Safe Drinking Water Act, 2002* (Ministry of Environment, 2007a; and Ministry of Environment, 2007b) and performance measurement programs (e.g., Burke, 2005) – will create a proliferation of data. Municipalities operate independently and employ a variety of proprietary and non-proprietary database systems to store infrastructure and projects related data (Halfawy et al. 2006a; Halfawy et al. 2006b; and Newton and Vanier, 2005). This results in *data representation heterogeneity,* that is defined as “the differences in data models, schemas, naming conventions, and levels of abstraction for conceptually similar data” (Sujansky, 2001; Wang and Murphy, 2004).

Wastewater pipelines' rehabilitation and replacement decisions based on subjective CCTV inspections and inadequate data can have major socio-political, legal, technical, and financial implications. Chae et al. (2003) emphasized that without reliable condition assessment data, millions of dollars of investments in wastewater infrastructure management systems would be 'useless'. To improve existing knowledge and decision making with regards to wastewater infrastructure management, there is a dire need of high quality data on wastewater collection systems operating under a variety of environments.

This paper presents a case study regarding the formation of a collaborative research initiative to collect high quality condition assessment data on wastewater pipelines and elaborates the development of a wastewater collection network condition assessment database. Furthermore, it provides a conceptual framework and prototype to address the issue of aggregating data from disparate sources (e.g., organizations, systems and formats). This is required to understand the performance of wastewater pipelines under a variety of operating environments and to develop generalized wastewater infrastructure management solutions.

3.3 Development of Public-Private Partnership and Research Collaboration

In 2005, the City of Niagara Falls entered into a public-private partnership with PipeFlo Contracting Corp. to bring the first commercial Side Scanning and Evaluation Technology (SSET) camera to Canada. The City also collaborated with the Centre for Advancement of Trenchless Technologies (CATT), located at the University of Waterloo, to develop an asset management framework that would help the City to make cost-effective long-term network rehabilitation and replacement decisions. The SSET is being used to complete the first interior inspection of the City of Niagara Falls 412 km of wastewater collection network – the entire pipe network.

3.3.1 Background

The City of Niagara Falls wastewater network is approximately 412 km or 250 miles in length with a total replacement value of approximately $250 million (2004-05 dollars). The average age of manhole to manhole pipe section in the system is 43 years with the oldest pipes built in the mid to late 1800s.

From the late 1990s, the City of Niagara Falls focused considerable resources in the areas of sewer, water and road asset inspection and management programs. The proposed changes to Ontario Provincial Legislation, specifically *Bill 175, The Sustainable Water and Sewage Systems Act, 2002* (Ministry of Environment, 2002) forced the City staff to investigate methods for assessing the structural integrity of their sewer and water systems in terms of their long-term ability to maintain service levels. An analysis – performed by the City staff based on simple linear deterioration model and present (year 2004-05) capital spending levels – established that every City owned sewer line section should last in excess of 175 years.

Dwindling sewer Closed Circuit Television (CCTV) inspection budgets from the mid 1980's to mid 1990's made the task of network repair and replacement prioritization next to impossible. Increased competition and consequently lower than market unit prices in the sewer CCTV inspection industry also led to less than desirable results in terms of inspection and report quality. The bulk of the inspection data collected during the 10 year period was of little use for comparative analysis due to the fact that less than 6% of the system was being inspected per year with widely varying reporting and inspection qualities.

Attempts at standardization of operator certification and defect coding in accordance with WRc (Water Research centre, UK) 3rd edition of the Manual of Sewer Condition Classification (MSCC) did marginally improve the results. However, the CCTV output was still highly dependent upon camera operators and their interpretation of the contract language and coding requirements. The issue of defect change over time was also of prime importance because the review of duplicate CCTV inspections – performed approximately 10 years apart – provided little information about defects' progression.

In 2002, the Niagara Falls City Council, faced with the impending sustainability legislation, authorized substantial increases to the Municipal Utility Budget to allow for the inspection of a larger portion of the system. Councilors were presented with the reality that the City-owned wastewater assets would have to be inspected and monitored on a more frequent basis and a suitable rehabilitation plan needed to be formalized, given the capital budget restrictions, to ensure the viability of the system over an extended service life.

3.3.2 Needs Assessment and Technology Review

In May of 2005, the City Staff began to research the issue of repeatability of both, the raw inspection product and associated reports, as well as, the issue of the determination of defect progression or structural deterioration over time. The Centre for Advancement of Trenchless Technologies (CATT) was enlisted to assist the City in determining the functional needs of the City's proposed inspection program and the reporting requirements to support a long-term rehabilitation and sustainability plan for the City's wastewater network. To determine the feasibility of any proposed changes to the inspection equipment used or the product delivered, PipeFlo Contracting Corp., located at Stoney Creek, Ontario, was invited to join the research group. PipeFlo Contracting Corp. has more than 20 years of experience in pipelines inspection and repair industry, and it allowed the group to assess any proposed technology in the field.

For needs assessment, technology selection and research collaboration, a review of past inspection records and decisions was performed. Based on the analysis, following needs were identified:

1. The inspection technology must be capable of producing imagery that is spatially correct in order to support the analysis of defects progression over time – thus, necessitating a technology to deliver clear, consistent and reproducible product. The review of previous inspection reports showed that the traditional CCTV records were inadequate for this particular analysis due to variability in equipment and contractor.

2. The proposed technology should collect data in a uniform, repeatable and defensible manner on every pipe. Specifically, the wastewater pipelines inspections and reports must be operator-independent.

3. Data collected must be in a non-proprietary format in order to fit with the City of Niagara Falls existing asset management system(s).

4. Inspection program should be economically feasible for a five year period – that is, it would have to be delivered at or lower than the market rates.

5. The technology should be capable of showing the inclination or slope of a pipe when its field of view is obstructed due to submergence or debris buildup.

6. The system and software should be able to rate a pipe section in accordance with the WRc (Water Research Centre, UK) Sewer Rehabilitation Manual (SRM) 4th edition and support the planned capital works decision-making and management system.

3.3.3 Technology Selection

In 2004/05, the City, PipeFlo Contracting Corp., and CATT were introduced to the Sewer Scanning and Evaluation Technology (SSET) – a relatively newer sewer inspection camera that has been used successfully in a number of cities in the USA and Europe but not in Canada. In United States, Hydromax USA, successfully used the technology in a number of large scale projects.

SSET consists of a 360 degree fisheye digital scanner with mechanical inclinometer and gyroscope. The technology differs from CCTV in that it produces digital side scan of pipe wall instead of producing only forward looking continuous video film of the pipe. The digital scanner scans the pipe wall millimeter after millimeter to produce a continuous side scans of the pipe. The image is a composite of a series of images which are joined using the software. The 360 degree internal pipe surface can be viewed as an unfolded flat digital image as shown in Figure 3.2. Online location data is collected using two different measurement systems. The inclinometer measures and records vertical movement while the optional gyroscope measures and records horizontal movements. The distance from the starting point is determined using a cable footage counter.

All images collected are spatially correct and provide the end user with an operator independent assessment of pipe, complete with a profile indicating measured inclination via an on-board inclinometer. Coding of images and production of reports is a post inspection process. It should be noted that little or no intervention by operator during inspection is required as there are no requirements to pan or tilt the camera head. The camera is simply driven through the sewer sections at a consistent speed. The camera and a sample image are shown in Figures 3.3 and 3.4, respectively

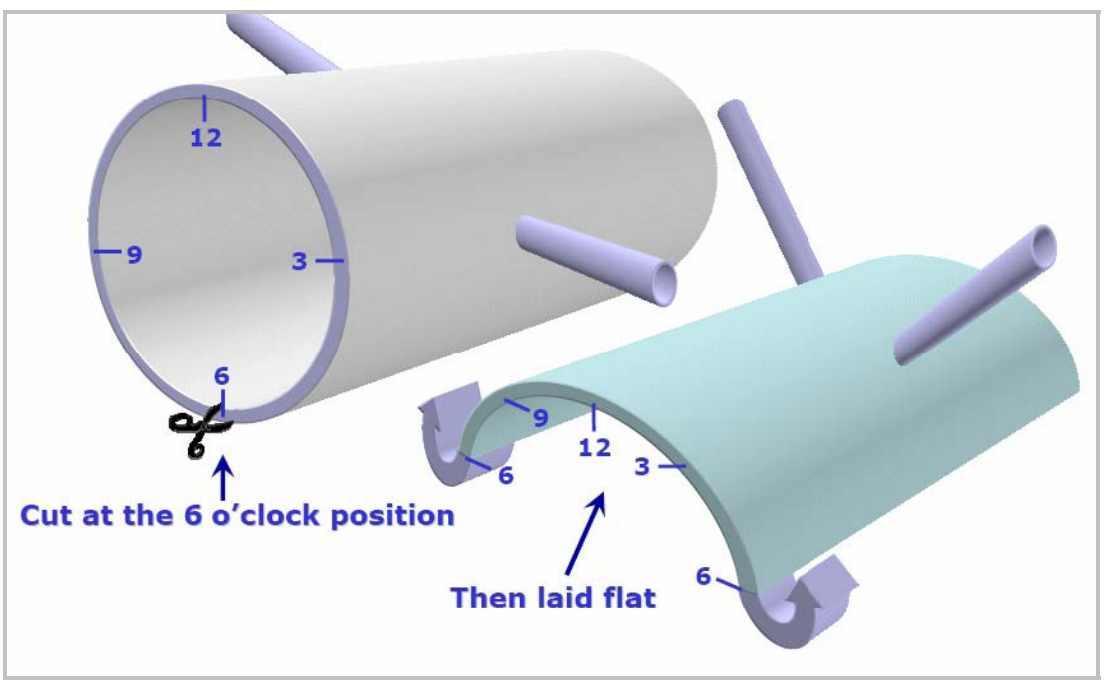


Figure 3.2: Unfolding of SSET Image (Blackhawk-PAS, 2001)

Figure 3.3: PipeFlo Contracting Corp. and the City of Niagara Falls Owned SSET Camera

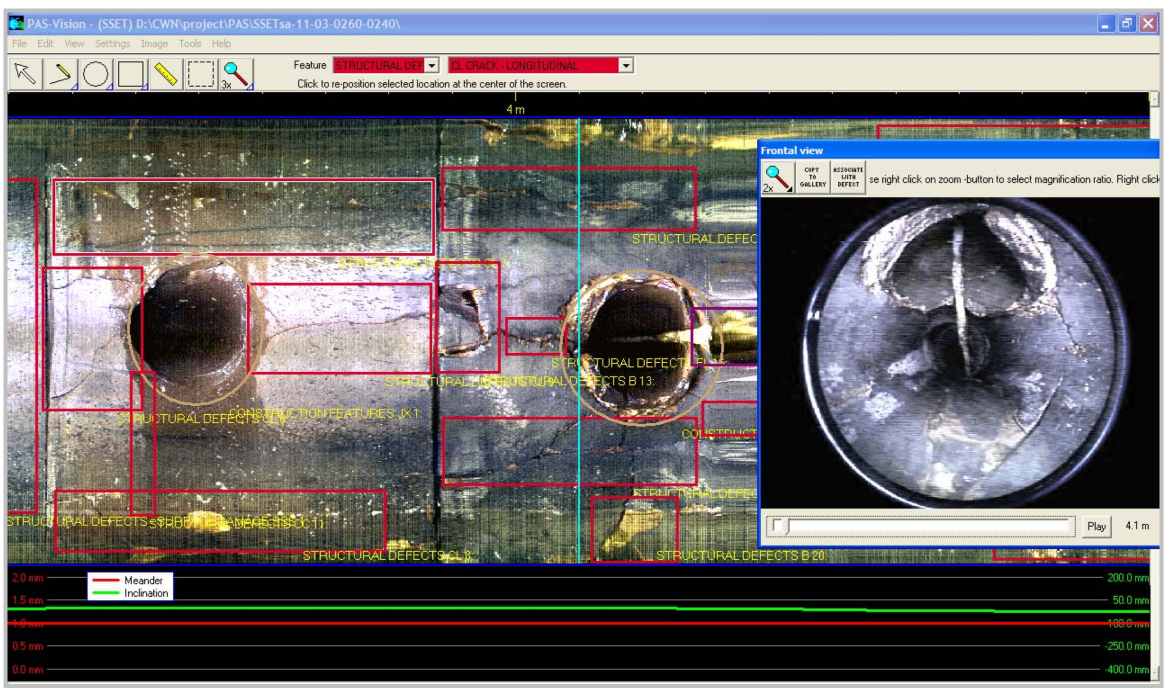


Figure 3.4: SSET Sample Imagery Obtained From the City Of Niagara Falls

A market survey revealed that the SSET camera and related software were not available in Ontario or other parts of Canada. In addition, a supporting software application for pipelines' condition rating and development of capital works program was required.

3.3.4 Public-Private Partnership

To introduce the SSET technology to the Canadian municipal market and to address software and technical issues, a partnership between the City of Niagara Falls and PipeFlo Contracting Corp. was formed. It was determined that the proposed venture would require an investment from all parties, both financially and in-kind contributions of staff time. Additionally, all parties were to assume some of the inherent risk related to the project.

PipeFlo Contracting Corp. and the City of Niagara Falls staff sourced a suitable SSET system in Atlanta, Georgia, and visited the vendor to determine the overall condition of the equipment. The truck and equipment complement was for sale for approximately $125,000 USD.

It was determined that the purchase cost of the equipment was prohibitively expensive for an all-out independent purchase by the Contractor – the unit rates for inspection would not allow for the completion of the inspection program within the prescribed budget amount of C$1.25 million.

In January 2005, a five year formal partnership agreement was signed between the City of Niagara Falls and PipeFlo Contracting Corp. with the assistance of a qualified lawyer. The agreement was structured to allow for the distribution of risk and reward between both parties. Under the agreement, the partners agreed to equally share the capital cost of the equipment and future revenues generated from sewer inspections in other jurisdictions. The perceived benefits and terms-of-service outlined in the legal agreement binding on both parties are described below.

The City of Niagara Falls in return for its contribution to the capital cost of equipment would recognize the following benefits:

- A fixed and lower than market rate for inspections – that is, $2.50 per meter ($0.76 per foot) – for the full five year length of the contract indexed to the rate of inflation. The rate includes three passes of high pressure water flushing of the line being inspected.

- Priority service with respect to the cleaning and inspection of sewers in the City of Niagara Falls over the length of the contract.

- Recovery of the City's initial investment – 50% of the capital cost of the equipment – when the system is used in other locales. In essence, the City of Niagara Falls receives a percentage in the form of a rebate to a maximum of $125,000 USD when the equipment is in-service for other municipalities or commercial customers.

PipeFlo Contracting Corp. recognizes the following benefits in return for its monetary and technical contributions:

- Interest free loan of 50% of the capital cost of the equipment for five years.

- An exclusive contract for five years with the City of Niagara Falls to clean and survey 400 km of sewer for five years. The contract value is approximately C$1.25 million.

- Exposure to other municipal markets by virtue of the City of Niagara Falls being a reference customer for the technology.

Both parties successfully negotiated with the vendor for an exclusive right to operate the technology in the Southern Ontario marketplace for the length of the contract. It should be noted that the legal agreement outlining the terms of the contract and financial obligations of the parties was approximately 160 pages in length and took approximately 30 weeks to draft and finalize.

3.3.5 Research Added-Value

In November 2004, a research proposal was submitted to the Canadian Water Network (CWN) entitled: "Development of an Underground Wastewater Collection Network Asset Database and Management Framework." The Canadian Water Network received more than one hundred Expressions of Interest in response to the Strategic Research Call 2004/2005, out of which 48 were asked to submit full proposals. After peer review and careful consideration of the projects against the CWN stated goals and criteria, 22 projects were recommended for funding, and the "Development of an Underground Wastewater Collection Network Asset Database and Management Framework" was one of the selected projects.

The ultimate project goal was to develop a suite of tools which would provide the most cost-efficient and effective system of maintenance, repair and rehabilitation of wastewater collection networks, with the aim to guarantee security of sanitary sewage collection to meet social, health, economic and environmental requirements. It needed to be carried out within the context of integrated catchment management and the strategic objective of ensuring security of water resources. The specific goals for the project included:

- Development of a comprehensive non-propriety wastewater collection network asset management database using the relatively new Sewer Scanning Evaluation Technology. The resulting database should be easily accessible and upgradeable, and would contain key asset attributes, such as sewers' length, material, diameter, age, and structural and operational condition grades.

  Complete inventories and detailed condition assessments of water infrastructure facilities are crucial for estimating costs and for ensuring that rational repair and rehabilitation strategies are employed. Using the City of Niagara Falls as a beta-site, a non-proprietary asset database was to be developed, tested and evaluated. This would be the first known complete non-proprietary wastewater pipelines condition assessment database in North America.

- Development of protocols and algorithms that would ensure that accurate and high quality structural and operational condition assessment data is loaded in the asset database.

- Development of a management framework for wastewater collection networks.

  The framework would allow for the development of rational network maintenance, rehabilitation and replacement policies and priorities. The framework would help in devising least-cost rehabilitation alternatives to meet the desired structural, operational, hydraulic, and environmental performance requirements.

3.3.6 Project Challenges, Lessons Learned and Good Practices

It is not uncommon to face technical and management challenges in a large-scale project involving many stakeholders. This project was not an exception, and a number of challenges and issues were encountered – some of them unforeseeable and beyond control. The following paragraphs list some of these issues, and briefly discuss the lessons learnt and good practices for such type of collaborative projects.

1. The supplier firm disbanded immediately after delivering the SSET camera and computer system. Not only did the equipment turn out to be faulty but the supplier failed to provide the defects coding software. Despite the legal contract, the City of Niagara Falls and PipeFlo Contracting Corp. had no resources to chase down the supplier in the USA.

   Unfortunately, prior to 2005, there was only one SSET camera supplier in North America and, therefore, the risk of abandonment was unavoidable. The abrupt dissolution of firms – thought to be less likely in the past – is a real risk with the present state of economy and is difficult to predict. A thorough investigation about the supplier, equipment manufacturer, spare parts supply, and possible hardware and software issues will help to mitigate the risk of abandonment. Equipment should be checked on-site before delivery, and some of the supplier personnel should be available for the first few days of the project. Fortunately, the Centre for Advancement of Trenchless Technology (CATT) helped in finding and establishing the contact between the City of Niagara Falls, and Hydromax USA and Dataflo Inc. in the USA to secure defects coding software. It took PipeFlo Contracting Corp. a few months to replace special camera cables and lights to fix the hardware.

2. The defects coding software needed to be customized according to WRc Manual of Sewer Condition Classification (3rd edition) and the City requirements. (This was carried out by the author.)

3. In 2006, the Manager of Infrastructure Management at the City along with two key members of the project team left their positions to join a consulting firm. The City could not find proper replacements for one year. This adversely affected the field data collection as well as the implementation of project quality assurance and quality control protocols at the City. In fact, the data collection was halted for a number of months.

   This reveals management challenges from organizational viewpoint in replacing experienced staff. It is to be noted that quality assurance plan was kept enforced at the University of Waterloo, and no data with quality issues were allowed to be imported into the database. This created a discrepancy between the actual data collected in the field and the data present in WatBAMS.

4. At the end of 2006, OYO Corporation in Japan – the manufacturer of SSET camera – sold the technology and discontinued all the technical support and spare parts supply. PipeFlo Contracting Corp. was able to manufacture and source most parts for the camera

except the motherboard. The manufacturing of parts was expensive and resulted in longer downtimes.

5. It was determined that the City as well as the Contractor did not have proper arrangements for data storage, and twice lost substantial amount of data due to computer hardware problems.

   A well documented and suitable data management plan should be established before embarking on data collection. The plan should list the responsibilities and contain information about data flow, physical storage, and safety and security of hard-earned data. Two dedicated data servers for this project at the University of Waterloo helped the City to recover the lost data, and thus saved hundreds of thousands of dollars of public money.

6. It appeared as if the City and Contractor established some unachievable targets (e.g., inspecting at least 1000 meters of pipelines per day) due to poor knowledge about the wastewater network. The Contractor determined that they were losing money due to low inspection rates and high expenses.

   Unfortunately, this is a typical situation in this industry and shows lack of due diligence on the part of contractors. When treading an unknown territory – that is, wastewater pipelines – with little or no knowledge about their condition, it is usually helpful to be excessively cautious with respect to achievable targets and real costs.

7. In many instances, the wastewater pipelines were inaccessible due to excessive debris – probably never cleaned in their life-time – or needed bypassing arrangements due to high sewage flows. At some locations, cleaning and bypassing costs made the inspections three to five times costlier than the quoted rates.

8. An important issue impacting this type of collaborative research initiative stems from stakeholders' – sometimes – conflicting preferences and objectives. Due to technical, logistic, political, and monetary concerns, the City and Contractor tended to follow their own inspection program. Supplementary information (e.g., soil maps, water table and sewer surcharge data etc.) was either non-existent or not readily available. This made the proper study design quite challenging.

3.4 Development of WatBAMS (Waterloo Buried Asset Management System)

Despite their enormous investments in buried infrastructure, municipalities in Canada and across North America lack standardized and reliable methods for wastewater pipelines' condition assessment. A standardized and consistent approach to data collection would help municipalities and other levels of government to evaluate the needs of different municipalities and to share information on how to manage these valuable assets. Current standardization efforts are hampered by the lack of an accessible database of consistent quality. Data collected using the SSET camera provides accurate information about the location of various defects, as well as, the physical condition of each pipe in the network. This information is coded into WatBAMS, a relational database, using WRc's sewer condition assessment protocols as specified in WRc (1993, 2004). WatBAMS provides tools for data exchange, quality assurance and quality control, data storage, analysis, information retrieval, and decision-making for wastewater pipelines' management. The data collected in this project will help to develop a standardized approach for assessing the performance and condition of the network, and for studying how the network deteriorates over time.

3.4.1 Establishment of Data Requirements

The minimum data requirements for developing an effective maintenance management system for wastewater networks are specified in Figure 3.5. The requirements were established from literature review (e.g., Davies, Clarke, Whiter, and Cunningham, 2001; Davies, Clarke, Whiter, Cunningham, and Leidi, 2001; WRc, 2001) and in consultations with industry professionals at various conferences and workshop meetings. The proper soil maps did not exist for the City, and therefore, the author reviewed more than three dozen geotechnical reports to collect and incorporate soil and groundwater information into the database. Clay, silt, and silty sand were found to be the predominant soil types, and water table was recorded below the sewer pipes in most of the cases.

A variety of wastewater pipelines were included with respect to age, material, size, and geometry as shown in Figure 3.6. The defined ranges for various pipelines' parameters cover majority of the gravity wastewater infrastructure in most of the municipalities.

3.4.2 Quality Assurance and Quality Control

According to Mitchell et al. (1985) and Taylor (1985), the quality of data can be judged on the basis of: (1) accuracy of identification of parameter to be measured; and (2) accuracy of quantification. An adequate quality data is consistent and exhibits small uncertainty with respect to requirements. Taylor (1985) defined *quality assurance* as “the operations and procedures which are undertaken to provide measurement data of stated quality with a stated probability of being right.” The *quality control* pertains to employing proper methodology, equipment calibration and proper usage (Taylor, 1985).

The Side Scanning and Evaluation Technology (SSET) used in the project provided consistently high quality imagery suitable for identification and marking of various structural and operational defects. This observation is in line with an earlier SSET evaluation conducted by the Civil Engineering Research Foundation (CERF) that concluded, “SSET images accurately depicted various defects, and the resolution and clarity of images were sufficient to indicate defects’ type and size correctly” (CERF, 2001). When compared to CCTV data, the CERF study found that SSET was best suited to identify structural defects, such as cracks, fractures, open and displaced joints, and operational defects, such as roots, debris and grease.

All the personnel handling data were trained and certified by NAAPI (North American Association of Pipelines Inspectors). NAAPI’s training and certification program in association with CATT was unique in North America – the only organization that provided this training until 2001 – and stipulated the Ontario Provincial Standards (OPS 409 specifications) for quality sewer inspections. The standard requires an accuracy of 95% for header, 85% for details, and the lowest acceptable tolerance is 75%.

To ensure high quality of collected data, a quality assurance plan was developed and implemented. Amongst other things, the plan specified requirements with respect to pipelines cleaning, bypassing, coding, and acceptance of surveys. To ascertain the correctness of defects coding, a number of pipe samples were coded and classified by the author and personnel from Dataflo Inc., USA, PipeFlo Contracting Corp., Canada, and the staff at the City of Niagara Falls. After several meetings and coding exercises, a consensus was achieved and the rules and procedures were documented to ensure consistent defects coding and to resolve future quality related issues.

The inspections were checked for accuracy, and the surveys failing the check triggered additional verifications on inspections performed during that period of time. Further quality assurance and quality control, and security procedures are implemented during the import of coded survey data into the database and described in Sections 3.4.2 through 3.4.5.

3.4.3 Pipeline Inspections and Defect Coding

The defects coding of surveyed data is carried out using PAS Vision ™ (Ve1.24.3a) software developed in conjunction to be compatible with SSET camera files. The defects coding in PAS Vision ™ can be customized to conform to various condition assessment protocols, for example, PACP, or WRc etc.

The author customized the PAS Vision ™ software coding system to defect codes as specified in the 3rd edition of WRc's Manual of Sewer Condition Classification (WRc, 1993).

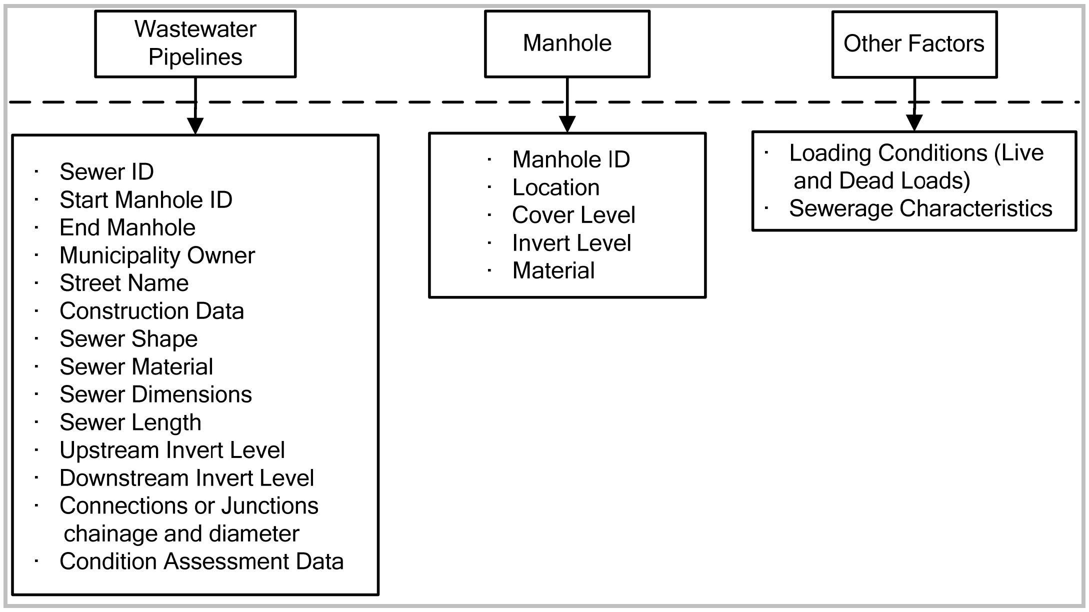


Figure 3.5: Minimum Data Requirements

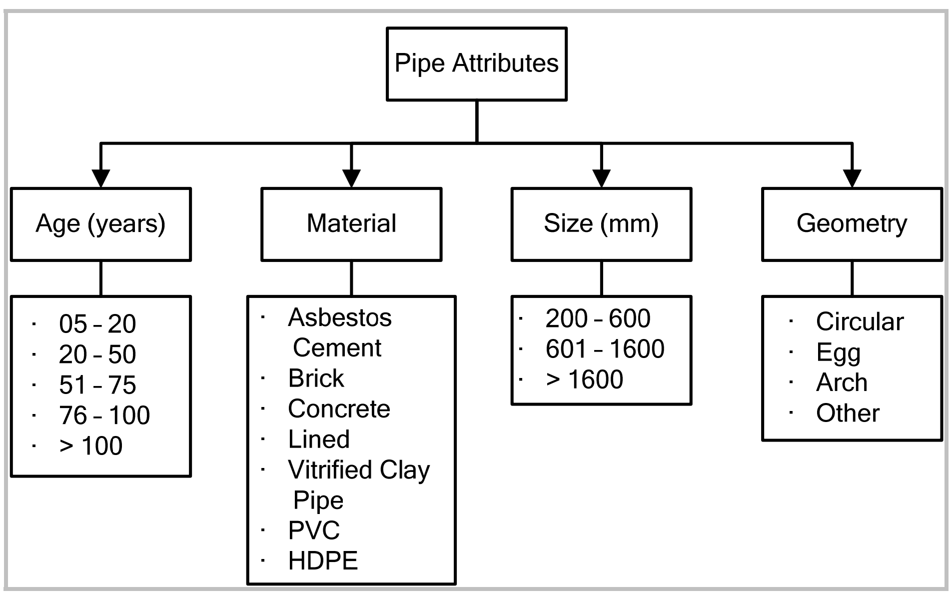
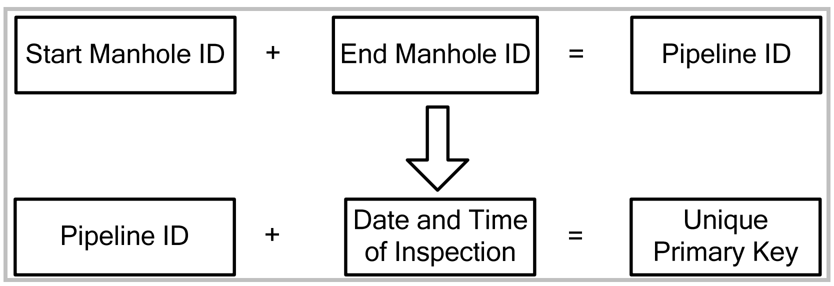


Figure 3.6: Pipe Attributes

3.4.4 Database Integrity and Consistency

The data redundancies and anomalies were eliminated by following standard database normalizing procedures called the Normal Forms. In particular, the following steps were followed to keep the database in consistent form, and to ensure data integrity and security.

1. *Unique Primary Key*: Primary key formed by concatenating pipelines ID with the date and time of survey uniquely identifies each entity, and its attributes. This allows multiple surveys on the same lines at different times to be uploaded into the database.



2. *Referential Integrity*: Referential integrity prevents inconsistencies in data stored in a relational database. Referential integrity rules ensure that database remains consistent during updating and deleting procedures. For example, in WatBAMS, the data import utility first checks the existence of an entity (pipeline) in the asset inventory, and imports condition assessment data only if it finds a matching pipeline ID in the inventory. This ensures that manhole IDs are properly marked in the field and drawings. Similarly if an entity is deleted from one table, say pipelines' 'Header' table, all the related entries in condition assessment and other related tables are deleted. This is called *cascading delete* operation. Similarly *cascading update* rule ensures that when a related field is updated in a table, all the relevant fields in related tables are updated.

3. *Error Checks and Error Handling*: During an import session, WatBAMS checks the PAS Vision ™ coded file(s) against the standard codes as provided in the 3rd edition of WRc Manual of Wastewater Condition Classification (WRc, 1993). Import session is terminated in case of any discrepancies in the coded file(s), and the database is not updated. Any changes to the database due to erroneous transactions are cancelled. The database is rolled back to previous consistent state and the application issues appropriate error messages. The particular data file(s) is checked, and appropriate corrections are carried out. The application successfully captured data inconsistencies such as defects coding carried out in different measurement units (i.e., metric Vs Imperial), or operators' mistakes, such as entering wrong manhole or pipeline IDs.

3.4.5 Database Security

User-level security is implemented to protect the data and application from accidental or intentional modifications and changes. User-level type of security provides the most restricted access over the database and its objects. The workgroup information file holding group and users' information and passwords is distributed with the WatBAMS installation package. The information contained in this file determines not only who can open the database, but also the permissions various users and groups have on the database objects.

To protect the WatBAMS source code and to facilitate later updates of application without affecting the data model, the database has been split into front-end application, and back-end database. When an update will be issued, users will be prompted to refresh the links to the underlying database. Furthermore, independent applications can be developed to work with the same database with the front and back split arrangement. Figure 3.7 illustrates the two database approach.

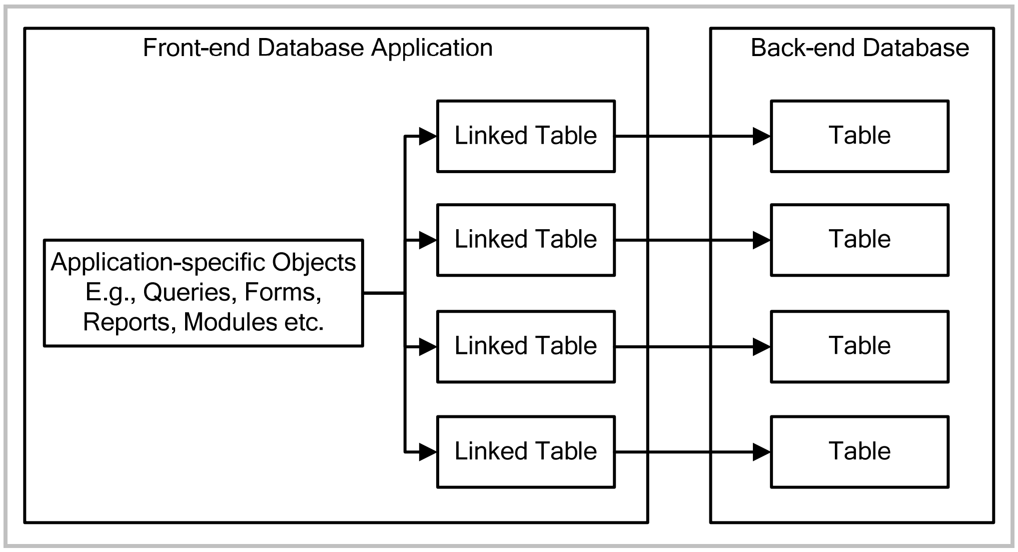


Figure 3.7: The Two-Database Approach (Microsoft Corporation, 2002)

3.4.6 Data Analysis and Data Processing

Figure 3.8 shows the data flow for data analysis and processing. The Data Exchange Utility in WatBAMS imports the PAS Vision ™ coded data into the database while ensuring data integrity and consistency as described in Section 3.4.4. WatBAMS assigns scores to each defect according to the 4th edition of WRc's Sewerage Rehabilitation Manual (WRc, 2001). Structural and operational internal condition grades (ICG) are determined based on peak, total, and mean scores for a pipe segment as specified in the WRc's Sewerage Rehabilitation Manual.

Data Exchange Utility provides the facility to import and process data in both single and batch modes. Data is uploaded into relevant relational tables maintaining referential integrity. A number of reports can be generated very easily, that include, for example:

- Current condition states for wastewater pipelines.
- Connection/junction report to locate lateral connections and their diameter.
- Defects histograms to give an idea of defects distribution along the pipe length.
- Identification of certain types of defects along the pipe length.
- Search capabilities in terms of database queries and data summaries with respect to individual pipe age, material, condition, etc.

Figure 3.9 presents a snapshot of WatBAMS showing the data import utility and various reports in a collage. Furthermore, the database integrates with the Manifold® geographic information system (GIS) used by the City. Figures 3.10 and 3.11 show an example of GIS soil map and spatial distribution of surveyed pipelines in various structural internal condition grades, respectively.

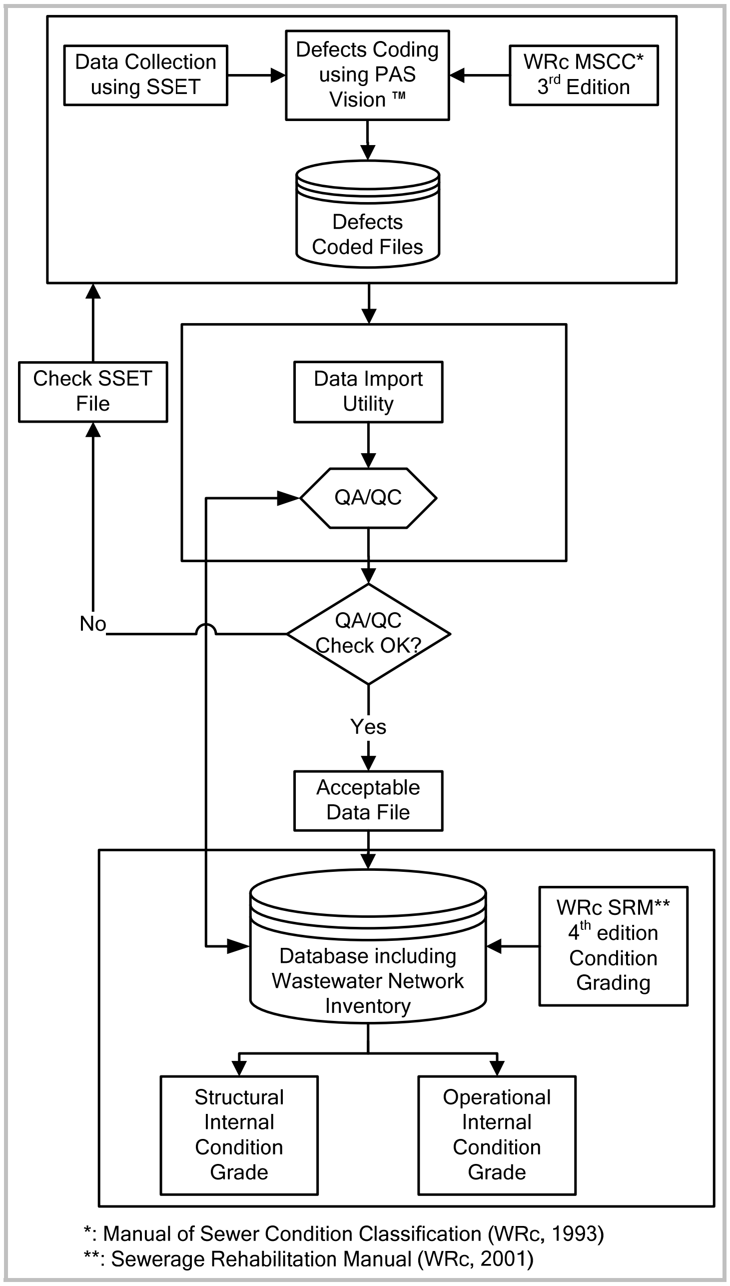


Figure 3.8: Data Flow Diagram for Data Analysis

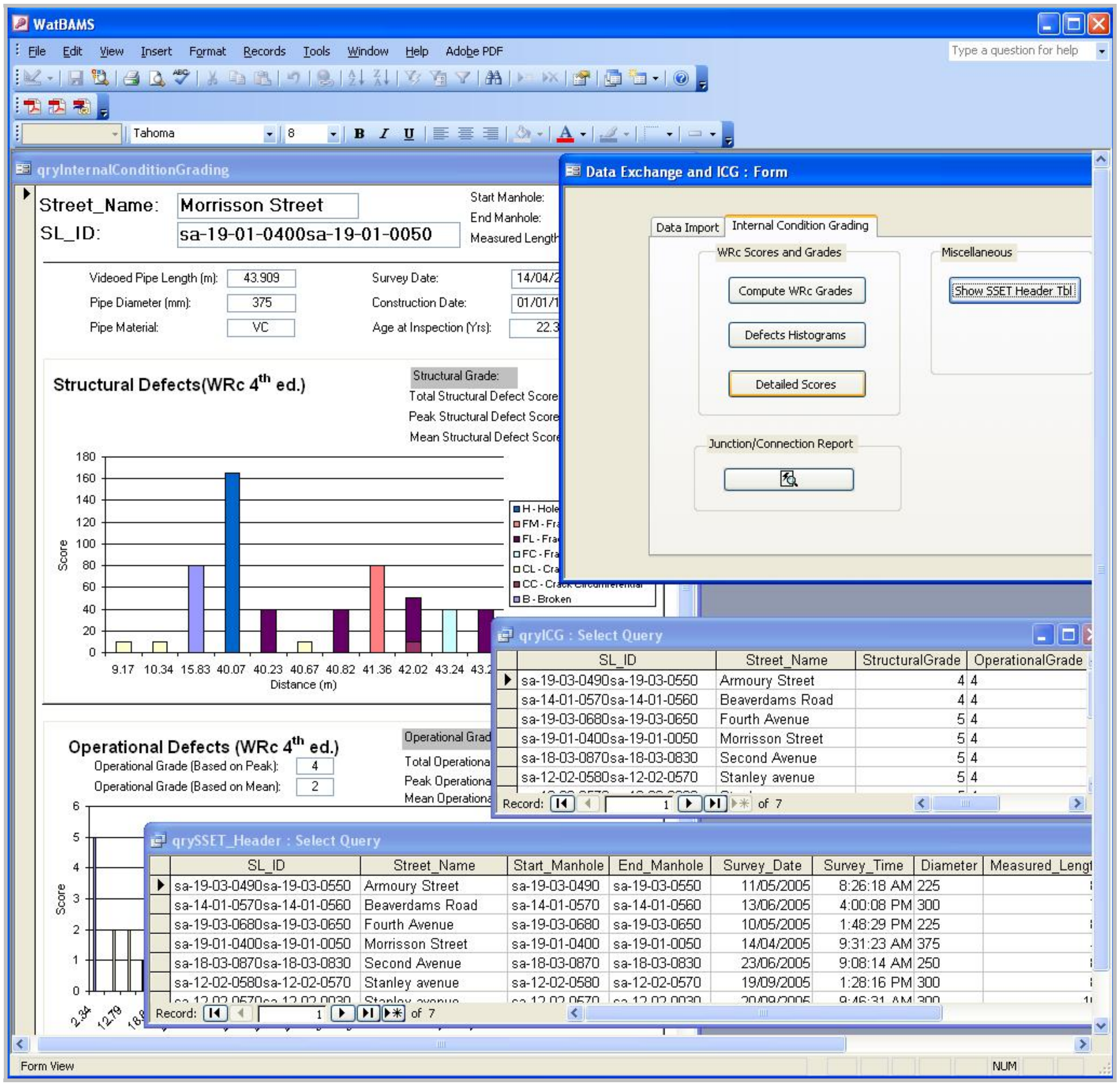


Figure 3.9: WatBAMS (Waterloo Buried Asset Management System)

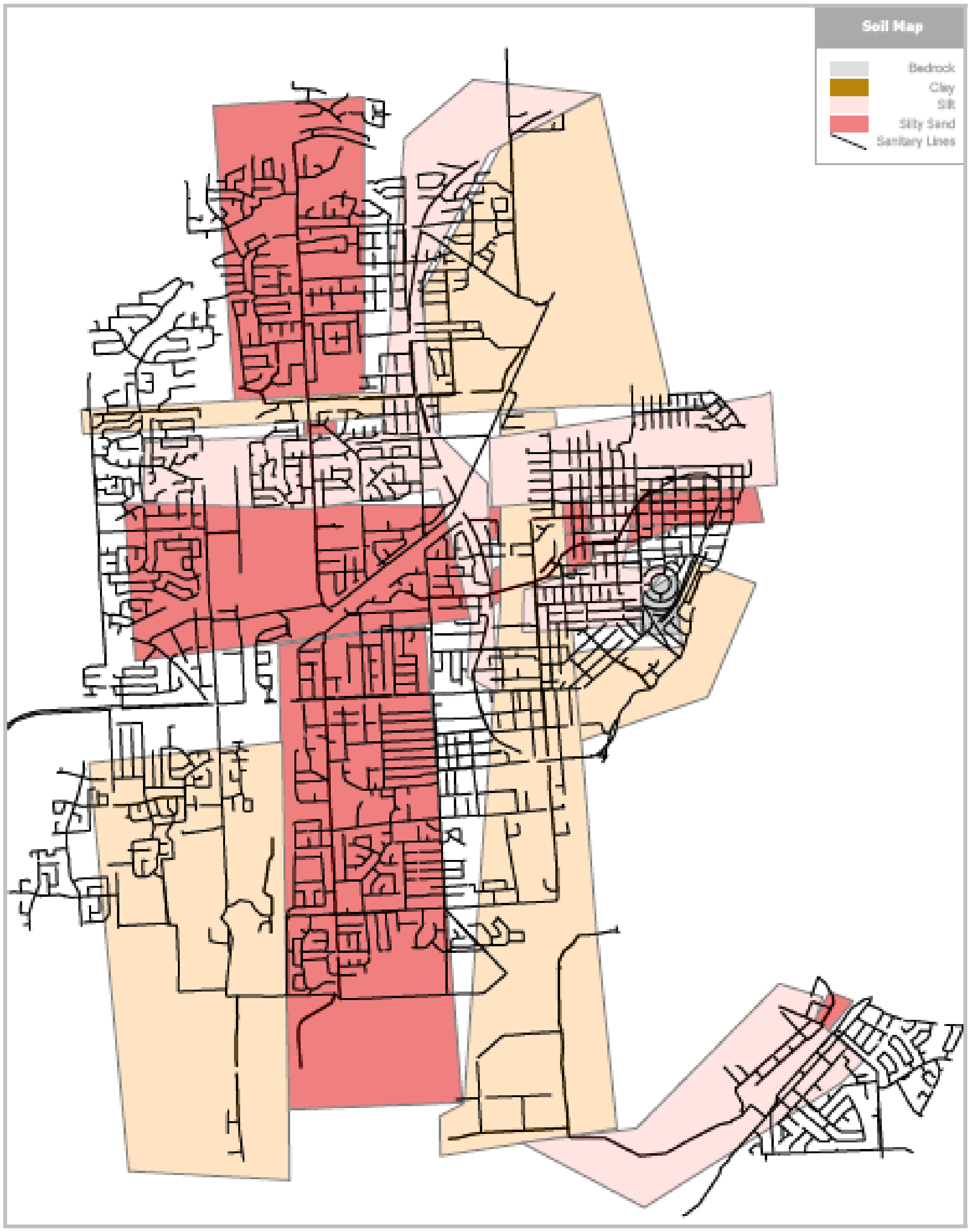


Figure 3.10: The Soil Map (developed using geotechnical reports)

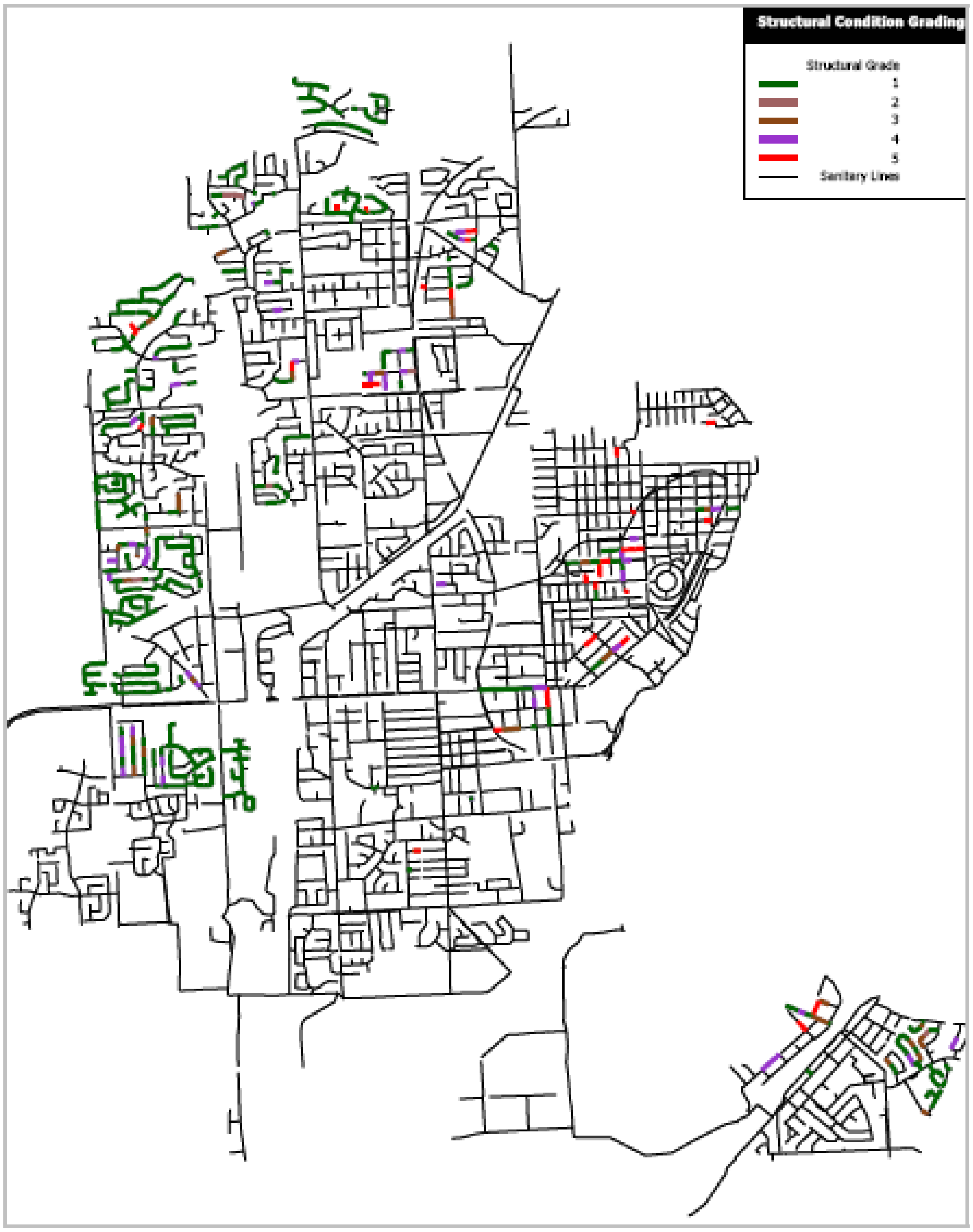


Figure 3.11: Spatial Distribution of Pipelines Structural Internal Condition Grades

3.4.7 Physical Data Storage

The surveys and condition assessment data are being stored on data servers at the City of Niagara Falls and the University of Waterloo. At the University, two data servers each configured under RAID 5 (redundant array of independent disks) back up each other in real time. Some advantages of this configuration include increased speed, reliability, data integrity, and fault tolerance.

3.5 Data Integration Framework

In 2003, the Canadian Society for Civil Engineering along with the Canadian Council of Professional Engineers, the Canadian Public Works Association, and the National Research Council of Canada proposed *Civil Infrastructure Systems Technology Road Map (TRM) 2003-2013* (CSCE, 2003). The first of the 10 major TRM objectives includes the development of a reliable asset inventory and condition database for Canada's infrastructure systems. In 2005, the Office of Wastewater Management of the US Environmental Protection Agency (USEPA) arranged an Advanced Asset Management Collaborative Working Session of 140 industry and academic experts from across the world to identify key pressing issues facing water and wastewater infrastructure management field (Agency, 2007). After two days of deliberations, the participants developed *top 10 action items* for advancing asset management in water and wastewater industry. The development of a central repository of high quality data was selected to be one of the most important items on the top ten list.

Municipalities and utilities, responsible for operating and managing wastewater infrastructure, function independently to meet data needs according to their specific business plans at local levels. According to Connery (2008), ". . . planning and organizational framework for addressing them [infrastructure problems] is fractured among welter of well-insulated institutions and political jurisdictions with little inclination and few incentives to collaborate." It is not uncommon to find different utilities using different tools (e.g., software systems, condition assessment technologies and protocols, organizational structures etc.) to manage their systems. This results in disparate data formats and data models, and creates data representation heterogeneity.

The development of a central repository of high quality data – by integrating multiple heterogeneous databases – is very important and critical to advance asset management sciences. For example, it will: (1) provide required data to improve information and knowledge related to performance behaviour of wastewater collection systems in different operating environments; (2) provide much needed data for basic research in the wastewater infrastructure management field; and (3) result in the development of better, efficient and effective management strategies. The following sections provide a brief overview of database integration types and methodologies, and present a framework and example implementation to integrate infrastructure management data from wastewater collection systems at various municipalities.

3.5.1 An Overview of Database Integration – Techniques, Types, and Issues

The problem of data integration from heterogeneous and independently maintained database systems has been studied in Computer Science, Bioinformatics, Biomedicine, and Health Informatics literature (see for e.g., Bright et al., 1994; Castano and De Antonellis, 1999; Dey, 2008; Marenco et al., 2004; Ouksel and Ahmed, 1999; Siepel et al., 2001; and Sujansky, 2001).

The techniques for database integration include the traditional Data Warehouse and Federated Database approaches, and a relatively new Semantic Web approach (Baker and Cheung, 2007). In case of *data warehouse approach*, data from various sources is translated into a local data warehouse – thus, also known as data translation strategy. Wang and Murphy (2004) referred to this methodology as Global-Schema or Schema Integration approach where schemas from autonomously managed local databases are combined after resolving semantic and syntactic differences. It involves manual or automatic data translation and transformation from various native data formats to a common format. The *federated database approach* involves query translation through a mediator on source databases, and is known as query translation strategy (Baker and Cheung, 2007; Sujansky, 2001). The *semantic web approach* goes beyond data model and uses standard ontologies to integrate various databases (Baker and Cheung, 2007).

According to Sujansky (2001), heterogeneous database integration may include: (1) vertical integration; (2) horizontal integration; and (3) integration for application portability. Vertical integration involves combining of semantically similar data from heterogeneous sources, whereas horizontal integration consists of aggregating complementary data from heterogeneous sources. For example, aggregating pipelines attributes (e.g., material, diameter etc.) from wastewater collection systems from different municipalities entails vertical integration, and compiling data from different information systems (e.g., financial, accounting, human resources, assets inventory, and GIS) at the same organization calls for horizontal integration. Integration for application portability involves standardized access to semantically similar information across organization.

According to Ouksel and Ahmed (1999), all of data integration approaches have their advantages and disadvantages and, despite extensive efforts, seamless data and knowledge integration is a baffling task. Sujansky (2001) emphasized that database heterogeneity will *never* be eliminated, and therefore, a single standard data model will never emerge for a specific field. Some of the grand challenge problems in database integration include (Sujansky, 2001): (1) resolving data representation heterogeneity; (2) database performance optimization; and (3) efficient maintenance of mappings among databases that are independently managed and changed frequently.

In the Civil infrastructure management field, majority of the efforts have been concentrated on: (1) developing standard data models for civil infrastructure management systems; (2) horizontal data integration within an organization – that is, data sharing amongst various departments; and (3) interoperability of software tools. Halfawy et al. (2007) provided an overview of *several* published data modeling and exchange standards for municipal infrastructure systems. Halfawy (2008) proposed a data integration and software interoperability solution for coordinating infrastructure management processes within an organization. Osman and El-Diraby (2006) presented an ontological model to support design coordination of utilities within urban transportation corridors.

The public works departments and agencies responsible for managing wastewater infrastructure at the municipalities operate independent from each other. This is also true in the United States (Wirahadikusumah et al.,1999) and many other parts of the world. To manage wastewater collection systems, each organization defines its own data needs according to specific policies and business plans at local levels. Therefore, standardization of data models for wastewater infrastructure management is unlikely. Even if there is a consensus on minimum data requirements, and a standard data model for wastewater infrastructure systems emerges in the future, representational heterogeneities with regards to data naming conventions and abstraction levels will stay. Therefore, data integration must match the industry's current business practices and future trends – that is, it is perceived that *organizations will continue to employ independently developed and maintained infrastructure management information systems and may collaborate beyond their institutional and geopolitical jurisdictions in the future.* Data exchange technologies, and proposed framework and prototype system, discussed in the following sections, can help in achieving this objective.

3.5.2 Data Exchange Technologies – Definitions and Specifications

XML (eXtensible Markup Language) is a technical specification officially specified by the World Wide Web Consortium (W3C) for data exchange and representation (W3C, 2009). XML technology is an open standard designed to be platform and application independent – that is, XML does not depend on the type of software and hardware platforms. XML has gained widespread popularity as data storage, transport, exchange, and presentation medium.

Some technical definitions and additional XML specifications are provided in the following paragraphs.

XML Schema Definitions (XSD)

XSD is a type of XML grammar used to describe structure of XML documents according to the specifications produced by World Wide Web Consortium (W3C). The basic XSD structures are <element> and <attribute> tags. XSD provides rules for developing valid XML documents, such as what elements may be allowed in XML documents, elements' attributes, types, and usage. XSD was developed to overcome some of the shortcomings of XML 1.0 Document Type Definitions (DTDs), that include (Cerami, 2005): (1) DTDs treat elements and attributes as strings whereas XML schema has built-in data types e.g., integers, floats and dates; (2) XML Schemas use XML syntax, however, DTDs have their own particular syntax; and (3) XML Schemas support more object-oriented practices, and provide additional validation rules and full support for XML Namespaces.

XML Parser (XML Processor)

An XML parser is a software engine such as a dynamic link library (DLL) used to read, update, create, and manipulate an XML document. A parser retrieves XML documents from a local system, determines the validity of XML documents with the given XML Schema, and delivers the document via a standard application programming interface. Hundreds of commercial, free and open source XML parsers exist (e.g., Microsoft Internet Explorer's built-in MSXML parser, Apache Software Foundation's Xerces XML parser etc.).

XSLT (eXtensible Stylesheet Language Transformations)

XSLT is a high-level declarative programming language specified by World Wide Web Consortium (W3C) for defining XML transformations. According to Brundage et al. (2000), XSLT – originally a part of XSL (eXtensible Stylesheet Language) – is very useful to interchange data between different computer systems. The development of an XML document involves: (1) transformation/conversion of one XML document into another; and (2) presenting that information. XSLT was developed to deal with the transformation and conversion tasks of preparing XML documents.

Figure 3.12 illustrate the data transformation process. An XML parser reads a document into a source tree. An XSLT processor performs data translations/transformations according to rules expressed in XSLT stylesheet tree, and gives out result tree. A Serializer then turns the result tree into final document.

XML Parser, XSLT Processor and Serializer tools are often bundled into a single product (Brundage et al., 2000). A number of readily available XSLT processors exist, such as MSXSL – Microsoft's XSLT processor based on MSXML 4.0, Xalan – Apache's open source XSLT transformation tool, and Instant Saxon – Michael Kay's Windows-executable XSLT processor.

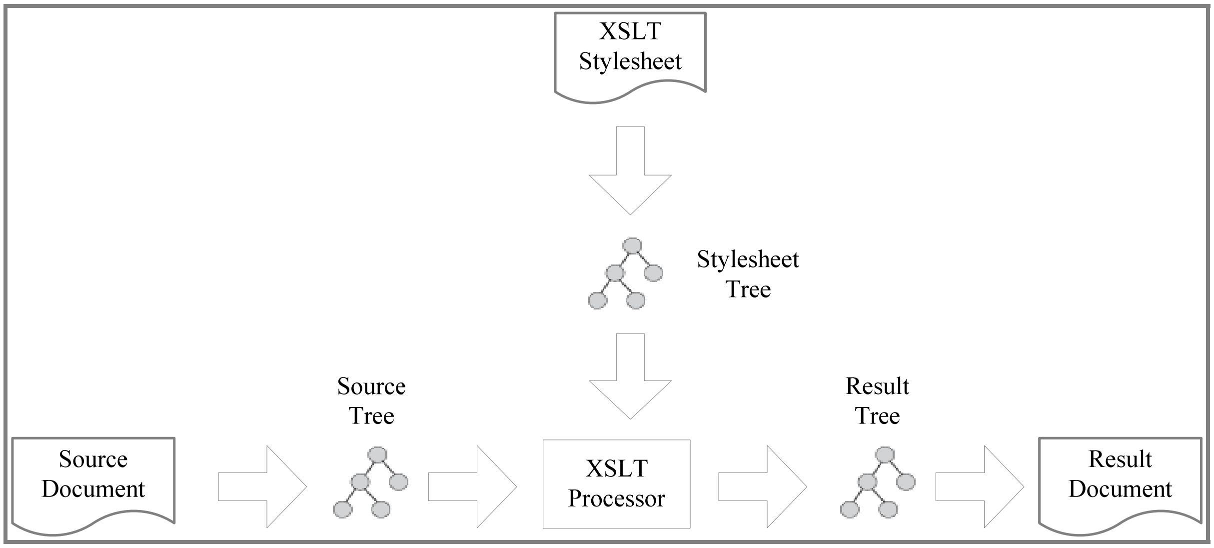


Figure 3.12: Data Transformation Process (adapted from Brundage et al., 2000)

3.5.3 Data Integration Workflow

Figure 3.13 presents the proposed framework for wastewater infrastructure management information systems' integration based on Global-Schema approach. It consists of the following steps:

1. Obtain source database or data in any format (preferably XML). Almost all the database management systems and applications can deliver data in XML format.

2. Use relevant schema file XSD to create structural tree diagram of a particular XML instance. The XSD file represents the structure of an XML document without data, and database management systems have the ability to produce schema file relevant to an XML instance. Otherwise, XML schemas can be designed using freely available XML

editors, such as Microsoft's XML Notepad, or any ordinary text editor, e.g., Notepad application.

3. Input the XML and relevant XSLT stylesheet files to XSLT processor, and an output XML file is produced based on the instructions inside XSLT stylesheet file. XSLT stylesheets are XML documents and use XPath query language to access data in source documents.

4. The output file is stored into a relational database system for further processing.

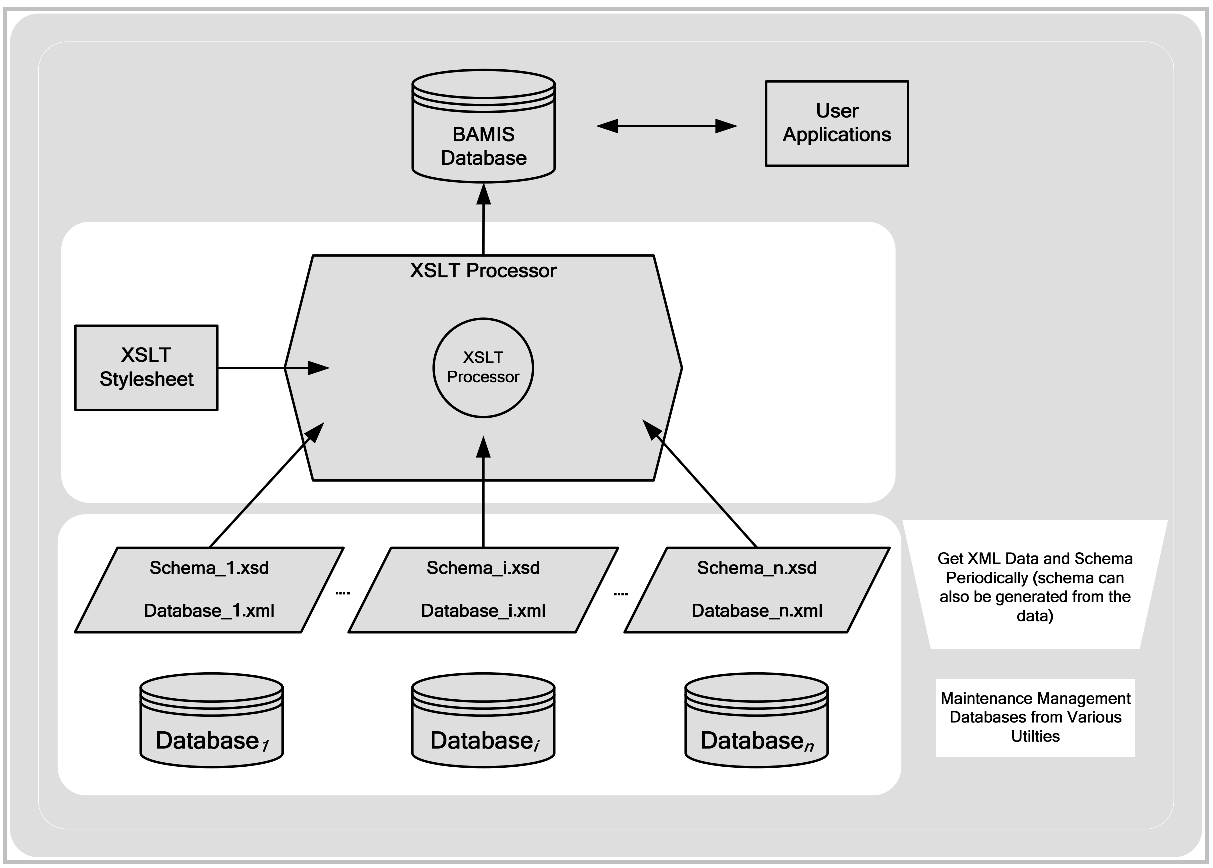


Figure 3.13: Database Integration Process

3.5.4 Rationale for the Proposed Data Integration Approach

The hybrid architecture – relational database along with XML technologies – and global-schema (i.e., schema integration approach) for wastewater infrastructure data integration is preferred for the following reasons:

1. Data source access is one of the most critical issues and the first step in data integration. As discussed earlier, utilities in Canada (and elsewhere) are reluctant to share data beyond their organizational and geographical confines. They are hesitant to provide access to their infrastructure management systems due to security risks as well as software and hardware restrictions. Therefore, mediator systems based on query translation on source databases are not feasible. Programmable ad-hoc query interfaces provide another data access alternative to get data in XML format over the internet. This approach will require additional resources on part of utilities, and without any incentives (e.g., additional resources) they are reluctant to take part in such initiatives. Under these circumstances the only viable remaining options to data access are based on: (1) downloadable files; or (2) manual data transport on portable hard drives.

2. Majority of the urban infrastructure data is stored in relational databases, and XML is an international standard for data representation and exchange that is independent of software and hardware platforms. Infrastructure asset management data, such as asset inventory and condition surveys, are not as complicated as the data encountered in other disciplines (e.g., life sciences or bioinformatics). By nature, the data structure is neither complex nor subject to frequent changes.

3. Automated data translation techniques often depend on the availability of metadata or entities relations. This information may not be available in many cases, and therefore, manual intervention is required to define relations or to create mappings between data. The latest data integration approaches involving semantic web and ontologies also require ontology mapping to deal with semantic heterogeneity.

4. The global schema better handles semantic conflicts by developing a global knowledgebase and provides an integrated summary of information from all the local schemas (Wang and Murphy, 2004).

Based on the above mentioned points, schema integration (or data translation) approach is deemed useful for integrating data from heterogeneous wastewater collection systems.

3.5.5 Data Integration for Wastewater Infrastructure – Case Study

The proposed framework for data integration is used to develop BAMS (Buried Asset Management System) – a relatively simple and small-scale prototype wastewater collection systems data warehouse. To demonstrate the integration of data from heterogeneous systems, wastewater collection databases from the Cities of Niagara Falls and Winnipeg are used.

BAMS (Target Database) Architecture

BAMS is a relational database – relational models represent data in tables and columns – that implements XML (eXtensible Markup Language) technologies for accessing and sharing data. Figures 3.14 and 3.15 present entity-relationship diagram and visual representation of basic schema (i.e., design pattern) used in the BAMS prototype. For illustration, only four tables – BAMS_tblCity, BAMS_tblSewerLine, BAMS_tblCondition, and BAMS_tblLocation – are used. In Figure 3.14, PK and FK represent primary and foreign keys to link the tables. Listing 3.1 provides a snippet of XML Schema definitions representing entities, attributes and types of attributes for BAMS database.

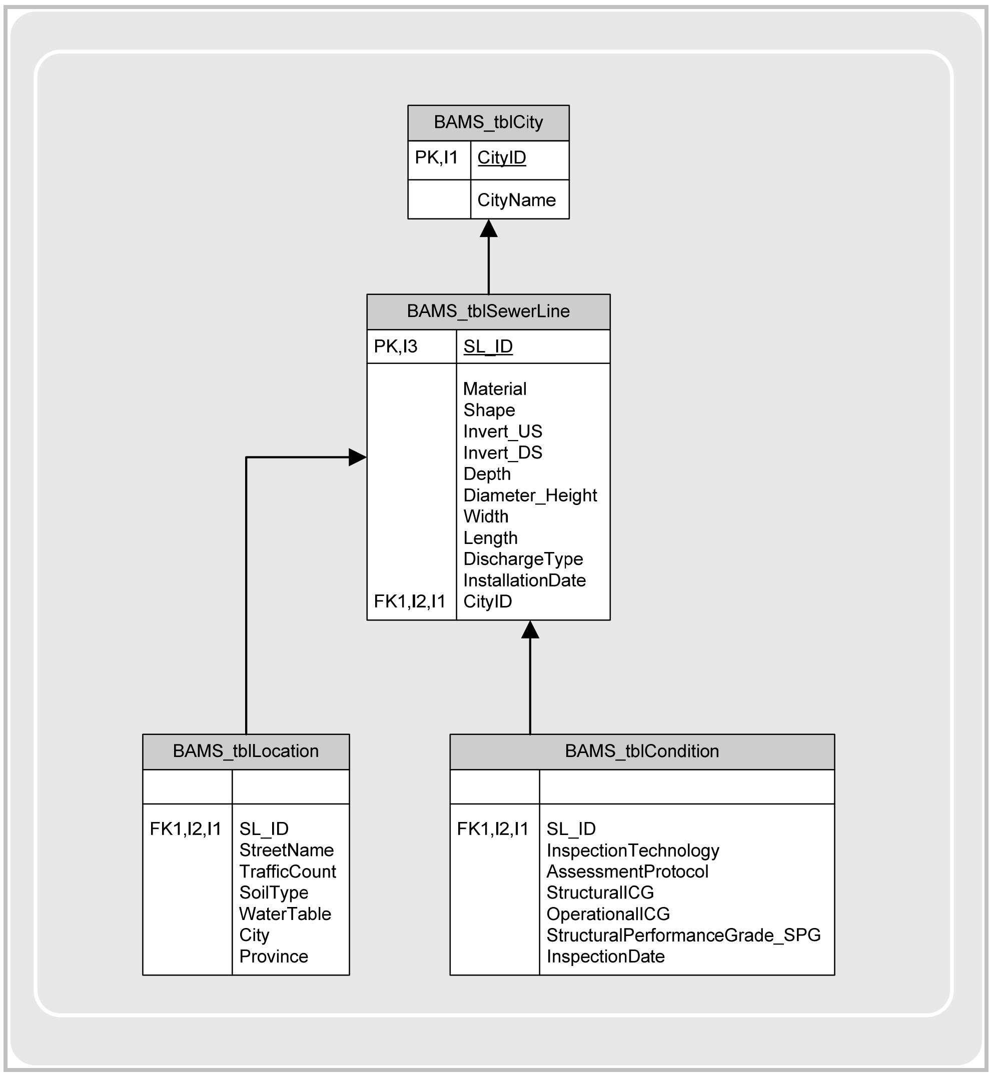


Figure 3.14: Buried Asset Management System Entity-Relation Diagram

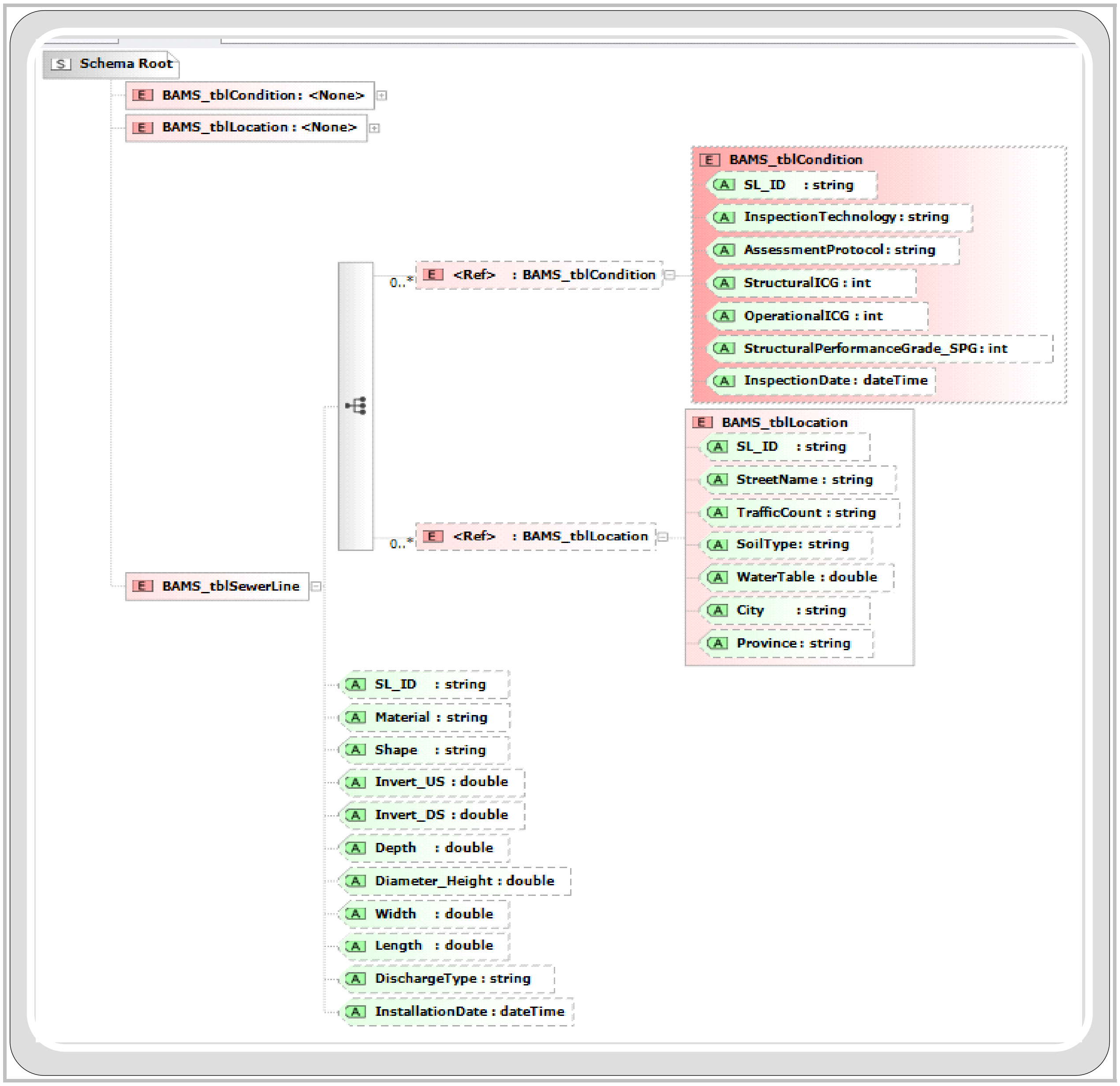


Figure 3.15: Buried Asset Management System Schema Definitions

Listing 3.1: A Snippet of BAMS Schema Definitions (BAMS.xsd)

```
<?xml version="1.0" encoding="utf-8" ?>
<xs:schema attributeFormDefault="unqualified" elementFormDefault="qualified"
xmlns:xs="http://www.w3.org/2001/XMLSchema">
  <xs:element name="BAMS_tblCity">
    <xs:complexType>
      <xs:sequence>
        <xs:element name="CityID">
          <xs:simpleType>
            <xs:restriction base="xs:int">
              <xs:minInclusive value="-2147483648" />
              <xs:maxInclusive value="2147483647" />
            </xs:restriction>
          </xs:simpleType>
        </xs:element>
```

…

```
<xs:element name="BAMS_tblCondition">
  <xs:complexType>
    <xs:sequence>
      <xs:element minOccurs="0" name="SL_ID" nillable="true">
        <xs:simpleType>
          <xs:restriction base="xs:string">
            <xs:maxLength value="50" />
          </xs:restriction>
        </xs:simpleType>
      </xs:element>
      <xs:element minOccurs="0" name="InspectionTechnology" nillable="true">
        <xs:simpleType>
          <xs:restriction base="xs:string">
            <xs:maxLength value="50" />
          </xs:restriction>
        </xs:simpleType>
      </xs:element>
```

…

```
<xs:element minOccurs="0" name="Material" nillable="true">
  <xs:simpleType>
    <xs:restriction base="xs:string">
      <xs:maxLength value="50" />
    </xs:restriction>
  </xs:simpleType>
</xs:element>
```

…

```
      <xs:selector xpath="BAMS_tblLocation" />
      <xs:field xpath="SL_ID" />
    </xs:keyref>
  </xs:element>
</xs:schema>
```

Source Databases

The City of Niagara Falls employs Municipal Infrastructure Data Standards (MIDS) (for details, see MIDS Tri-Committee, 2009) to manage physical infrastructure inventory. WatBAMS – the condition assessment database application developed by the author and described earlier – is integrated with MIDS to produce MIDS-WatBAMS source database for the City of Niagara Falls. The City of Winnipeg developed an in-house database application entitled Sewer Management System (SMS). Figures 3.16 and 3.17 show parts of E-R diagrams for SMS and MIDS-WatBAMS databases, respectively. It may be noted that the relations between different tables (entities) are defined in case of SMS whereas they are not specified – intentionally removed to increase complexity – in case of MIDS-WatBAMS database.

Data Integration

To transform data from SMS and MIDS-WatBAMS relational databases into BAMS database, the procedure specified in Section 3.5.3 and illustrated in Figure 3.13 is used. The schemas and XML documents from source databases and relevant XSLT files are turned into tree representation using an XML parser. Listing 3.2 and Figure 3.18 show a snippet of XSLT stylesheet and corresponding tree representation for SMS database transformation. For example, to resolve representational heterogeneity in *material* attribute between source and target databases, the grey highlighted instructions in Listing 3.2 search for material codes (e.g., AC, BR, VC, and CO) in the source document and translate/map them to the names used in the target document (i.e., Asbestos Cement, Brick, Vitrified Clay, and Concrete). The

XSLT processor thus transforms the source trees into the BAMS tree according to the rules and instructions – using XPath query language – in XSLT stylesheets. The resultant tree is converted to an XML document using a Serializer which is then saved into the BAMS relational database.

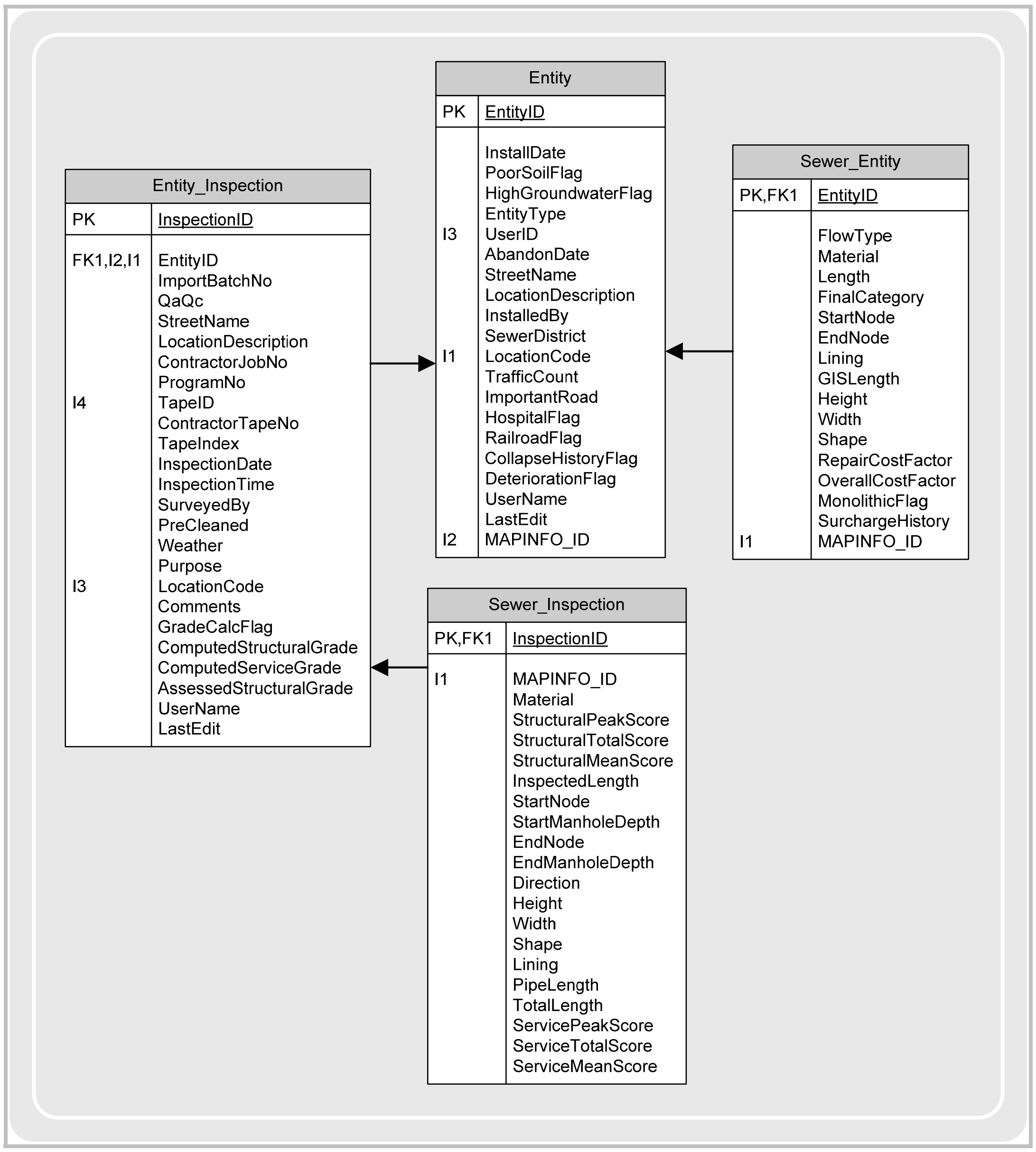


Figure 3.16: A Snippet of the City of Winnipeg Sewer Management System

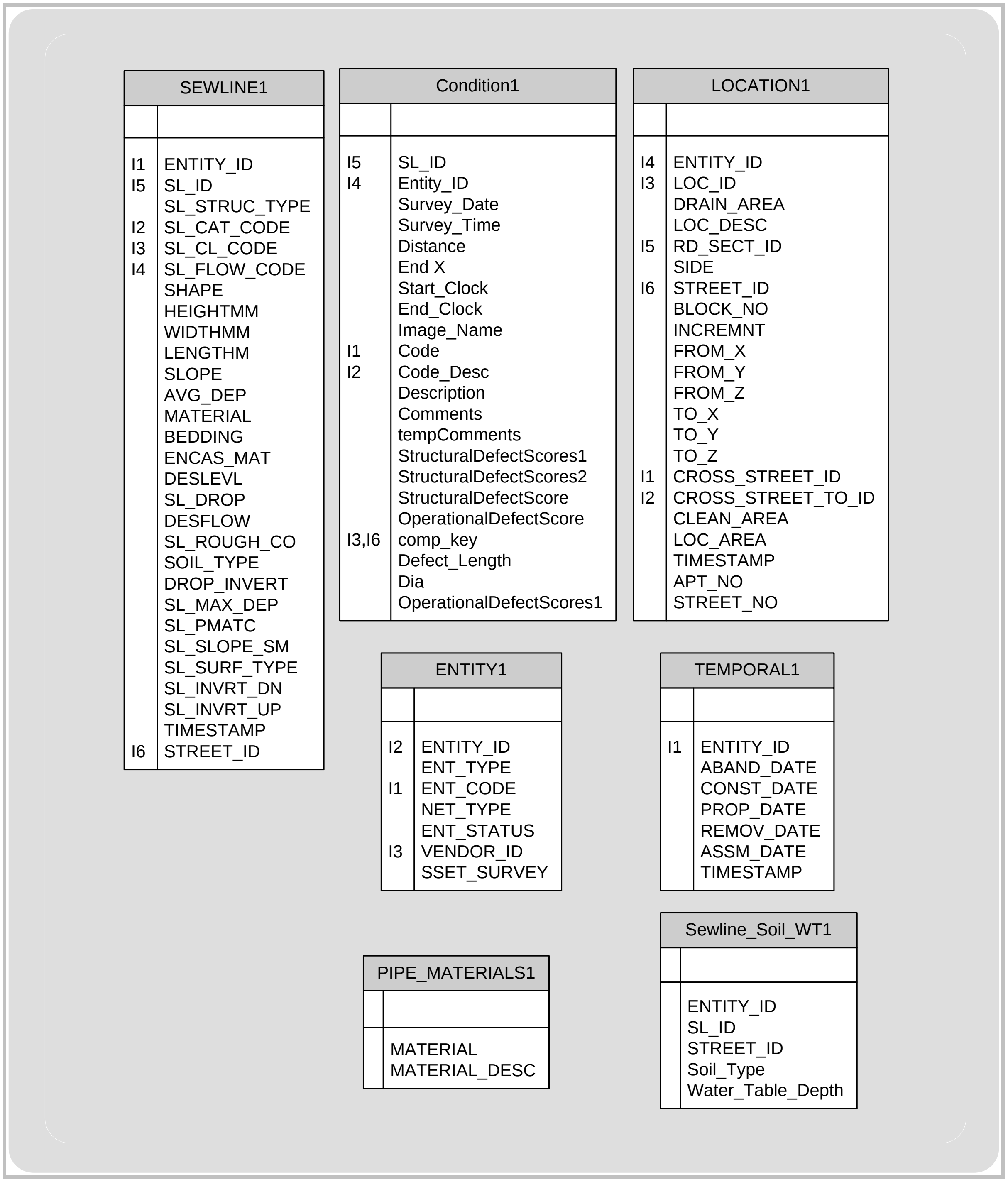


Figure 3.17: Part of the City of Niagara Falls MIDS and WatBAMS Databases

Listing 3.2: XSLT Stylesheet for SMS Database Transformation

```
<?xml version="1.0" encoding="UTF-8"?>
<xsl:stylesheet version="2.0" xmlns:xsl="http://www.w3.org/1999/XSL/Transform" xmlns:xsi=
    "http://www.w3.org/2001/XMLSchema-instance" xmlns:xs="http://www.w3.org/2001/XMLSchema
    " xmlns:fn="http://www.w3.org/2005/xpath-functions" exclude-result-prefixes="fn vmf xs
     xsi xsl">
    <xsl:template name="vmf:inputtoresult">
        <xsl:param name="input" select="()"/>
        <xsl:choose>
            <xsl:when test="$input='AC'">
                <xsl:value-of select="'Asbestos Cement'"/>
            </xsl:when>
            <xsl:when test="$input='BR'">
                <xsl:value-of select="'Brick'"/>
            </xsl:when>
            <xsl:when test="$input='CO'">
                <xsl:value-of select="'Concrete'"/>
            </xsl:when>
            <xsl:when test="$input='PE'">
                <xsl:value-of select="'Polyetylene'"/>
            </xsl:when>
            <xsl:when test="$input='PVC'">
                <xsl:value-of select="'PVC'"/>
            </xsl:when>
            <xsl:when test="$input='VC'">
                <xsl:value-of select="'Vitrified Clay'"/>
            </xsl:when>
            <xsl:otherwise>
                <xsl:value-of select="'Unknown'"/>
            </xsl:otherwise>
        </xsl:choose>
    </xsl:template>
    <xsl:output method="xml" encoding="UTF-8" indent="yes"/>
    <xsl:template match="/Import">
        <BAMS_tblCity>
            <xsl:attribute name="xsi:noNamespaceSchemaLocation" separator=" ">
                <xsl:sequence select="'C:/DOCUME~1/ryounis/Desktop/DATAAN~1/NEWFOL~1/bamsl
    .xsd'"/>
            </xsl:attribute>
            <CityName>
                <xsl:sequence select="'Winnipeg'"/>
            </CityName>
            <xsl:for-each select="Entity">
                <xsl:variable name="Vvar53_Entity" select="."/>
                <xsl:for-each select="Sewer_Entity">
                    <xsl:variable name="Vvar55_Sewer_Entity" select="."/>
                    <BAMS_tblSewerLine>
                        <xsl:for-each select="EntityID">
                            <xsl:variable name="Vvar58_EntityID_short" as="xs:short"
    select="xs:short(.)"/>
                            <SL_ID>
                                <xsl:sequence select="xs:string($Vvar58_EntityID_short)"/>
                            </SL_ID>
                        </xsl:for-each>
                        <xsl:for-each select="Material">
                            <xsl:variable name="Vvar62_Material_string" as="xs:string"
    select="xs:string(.)"/>
                            <xsl:variable name="Vvar64_result" as="xs:string?">
                                <xsl:call-template name="vmf:inputtoresult">
                                    <xsl:with-param name="input" select="$
    Vvar62_Material_string"/>
                                </xsl:call-template>
                            </xsl:variable>
                            <xsl:if test="fn:exists(fn:data($Vvar64_result))">
                                <Material>
                                    <xsl:sequence select="$Vvar64_result"/>
                                </Material>
                            </xsl:if>
```

Listing 2.2 Continued

```
                        </xsl:for-each>
                        <xsl:for-each select="Shape">
                            <xsl:variable name="Vvar69_Shape_string" as="xs:string" select↙
="xs:string(.)"/>
                            <Shape>
                                <xsl:sequence select="$Vvar69_Shape_string"/>
                            </Shape>
                        </xsl:for-each>
                        <xsl:for-each select="Width">
                            <xsl:variable name="Vvar71_Width_byte" as="xs:byte" select="xs↙
:byte(.)"/>
                            <Width>
                                <xsl:sequence select="xs:double($Vvar71_Width_byte)"/>
                            </Width>
                        </xsl:for-each>
                        <xsl:for-each select="Length">
                            <xsl:variable name="Vvar75_Length_decimal" as="xs:decimal"     ↙
select="xs:decimal(.)"/>
                            <Length>
                                <xsl:sequence select="xs:double($Vvar75_Length_decimal)"/>
                            </Length>
                        </xsl:for-each>
                        <xsl:for-each select="$Vvar53_Entity/Entity_Inspection">
                            <BAMS_tblCondition>
                                <xsl:for-each select="$Vvar55_Sewer_Entity/EntityID">
                                    <xsl:variable name="Vvar81_EntityID_short" as="xs:     ↙
short" select="xs:short(.)"/>
                                    <SL_ID>
                                        <xsl:sequence select="xs:string($                  ↙
Vvar81_EntityID_short)"/>
                                    </SL_ID>
                                </xsl:for-each>
                                <InspectionTechnology>
                                    <xsl:sequence select="'CCTV'"/>
                                </InspectionTechnology>
                                <xsl:for-each select="ComputedStructuralGrade">
                                    <xsl:variable name=                                    ↙
"Vvar87_ComputedStructuralGrade_byte" as="xs:byte" select="xs:byte(.)"/>
                                    <StructuralICG>
                                        <xsl:sequence select="xs:int($                     ↙
Vvar87_ComputedStructuralGrade_byte)"/>
                                    </StructuralICG>
                                </xsl:for-each>
                                <xsl:for-each select="ComputedServiceGrade">
                                    <xsl:variable name="Vvar91_ComputedServiceGrade_byte" ↙
as="xs:byte" select="xs:byte(.)"/>
                                    <OperationalICG>
                                        <xsl:sequence select="xs:int($                     ↙
Vvar91_ComputedServiceGrade_byte)"/>
                                    </OperationalICG>
                                </xsl:for-each>
                                <xsl:for-each select="AssessedStructuralGrade">
                                    <xsl:variable name=                                    ↙
"Vvar95_AssessedStructuralGrade_byte" as="xs:byte" select="xs:byte(.)"/>
                                    <StructuralPerformanceGrade_SPG>
                                        <xsl:sequence select="xs:int($                     ↙
Vvar95_AssessedStructuralGrade_byte)"/>
                                    </StructuralPerformanceGrade_SPG>
                                </xsl:for-each>
                            </BAMS_tblCondition>
                        </xsl:for-each>
                    </BAMS_tblSewerLine>
                </xsl:for-each>
            </xsl:for-each>
        </BAMS_tblCity>
    </xsl:template>
</xsl:stylesheet>
```

```
root
 |
 |___ element {http://www.w3.org/1999/XSL/Transform} stylesheet (QName xsl:stylesheet)
        |   \___ attribute  version = 2.0

. . .
                |___ element {http://www.w3.org/1999/XSL/Transform} template (QName xsl:template)
                |       |   \___ attribute  name = vmf:inputtoresult
                |       |
                |       |___ text \n\t\t
                |       |
                |       |___ element {http://www.w3.org/1999/XSL/Transform} param (QName xsl:param)
                |       |           \___ attribute  name = input
                |       |           \___ attribute  select = ()
                |       |
                |       |___ text \n\t\t
                |       |
                |       |___ element {http://www.w3.org/1999/XSL/Transform} choose (QName xsl:choose)
                |       |       |
                |       |       |___ text \n\t\t\t
                |       |       |
                |       |       |___ element {http://www.w3.org/1999/XSL/Transform} when (QName xsl:when)
                |       |       |       |   \___ attribute  test = $input='AC'
                |       |       |       |
                |       |       |       |___ text \n\t\t\t\t
                |       |       |       |
                |       |       |       |___ element {http://www.w3.org/1999/XSL/Transform} value-of (QName xsl:value-of)
                |       |       |       |           \___ attribute  select = 'Asbestos Cement'
                |       |       |       |

. . .
 |___ element {http://www.w3.org/1999/XSL/Transform} template (QName xsl:template)
 |       |   \___ attribute  match = /Import
 |       |
 |       |___ text \n\t\t
 |       |
 |       |___ element  BAMS_tblCity
 |       |       |
 |       |       |___ text \n\t\t\t
 |       |       |
 |       |       |___ element {http://www.w3.org/1999/XSL/Transform} attribute (QName xsl:attribute)
 |       |       |       |   \___ attribute  name = xsi:noNamespaceSchemaLocation
 |       |       |       |   \___ attribute  separator =
 |       |       |       |
 |       |       |       |___ text \n\t\t\t\t
 |       |       |       |
 |       |       |       |___ element {http://www.w3.org/1999/XSL/Transform} sequence (QName xsl:sequence)
 |       |       |       |           \___ attribute  select = 'C:/DOCUME~1/ryounis/Desktop/DATAAN~1/NEWFOL~1/bams1.xsd'
 |       |       |       |
 |       |       |       |___ text \n\t\t\t
 |       |       |
 |       |       |___ text \n\t\t\t
 |       |       |
 |       |       |___ element  CityName
 |       |       |       |
 |       |       |       |___ text \n\t\t\t\t
 |       |       |       |
 |       |       |       |___ element {http://www.w3.org/1999/XSL/Transform} sequence (QName xsl:sequence)
 |       |       |       |           \___ attribute  select = 'Winnipeg'
 |       |       |       |

. . .
```

Figure 3.18: A Snippet of XSLT Stylesheet Tree for SMS Database Transformation

3.6 Discussion and Conclusions

Historically, independent and non-standardized visual inspection approaches have been employed to inspect wastewater pipelines and assess their condition. Traditionally, municipalities employ a number of contractors – utilizing a wide variety of Closed Circuit Television (CCTV) cameras and condition assessment protocols – to investigate parts of their wastewater collection network. In the absence of proper standard requirements, the historic CCTV inspections – being highly subjective – resulted into inconsistent and poor quality data on video tapes. These tapes – some of them now digitized at additional costs – are very difficult and cumbersome to review. Majority of the infrastructure managers at the municipalities as well as researchers are frustrated with the poor quality of existing data and lack of real information on wastewater pipelines.

This paper presented a case study about the development of a collaborative research initiative to resolve the issue of scarcity of good quality condition assessment data on wastewater collection networks. A quality assurance and quality control (QA/QC) procedure was developed and built into the project plan to collect quality data on wastewater pipelines. Utmost care was taken to implement QA/QC procedure in the field and office. Using NAAPI (North American Association of Pipelines Inspectors) certified and trained personnel, state-of-the-art Side Scanning and Evaluation Technology, and wastewater collection network at the City of Niagara Falls, a high quality condition assessment database – WatBAMS (Waterloo Buried Asset Management System) – was developed. WatBAMS allows for the automatic generation of WRc pipe structural and operational performance grades and defects profiles directly from the native data files generated from the SSET camera system.

Additionally, procedures for quality assurance were implemented during in the data import utility, and data mining tools were developed in close co-operation with City of Niagara Falls and PipeFlo Contracting Corp. To integrate data from heterogeneous wastewater collection systems, a framework and prototype, BAMS (Buried Asset Management System), based on XML technologies was proposed.

WatBAMS provided useful data for the research presented in this thesis and will support future research in wastewater infrastructure management. The BAMS will provide the foundation to enhance our understanding about wastewater collection systems performance under a variety of operating conditions.

Formation of the research collaboration, public-private partnership agreement, and handling of subsequent technical and managerial issues was a long and complicated task. Issues with respect to training, data storage, equipment maintenance, staff turnover, and general familiarization with the inspection process and scheduling resulted in unproductive periods. The City Staff's concerns regarding acceptance of the reports were encountered. However, those were related to the acceptance of new product and cognitive issues with respect to the interpretation of reports. All the stakeholders agreed that the SSET camera offered far more detailed and objective view in terms of the inspection than standard CCTV cameras.

The research partnership with the University of Waterloo and the Centre for the Advancement of Trenchless Technology has been productive in developing a framework and related tools that helped the City to evaluate and manage their wastewater pipelines and to make infrastructure renewal decisions. It has also been helpful in the independent third party evaluation of technologies and pipe condition coding. The public-private partnership was a win for the City to get state-of-the-art wastewater inspections at or below current industry standard rates. It was also a win for PipeFlo Contracting Corp. as they have a guaranteed five year contract with the City of Niagara Falls. Without this long-term contract purchase of the SSET equipment would have been cost prohibitive. The development of high quality wastewater collection network asset database provides the foundation for present and future asset management research projects that were not possible due to non-existent or incomplete datasets.

Unfortunately, wastewater infrastructure management is far from reaping the benefits of recent technical advancements. Majority of the research work related to wastewater infrastructure management is carried out on ad-hoc basis with limited governmental funds or through multi-stakeholders' research initiatives. These initiatives and projects are not sustainable in the long-term and die down as they run out of funds within few years time. Similar to Long-Term Pavement Performance and National Bridge Inventory and Highway Bridge Programs, a long-term research initiative – with a sustainable funding mechanism – in buried infrastructure management is required.

Acknowledgment

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Chapter 4

Review of State-of-the-Art Statistical Deterioration Models for Wastewater Pipelines

4.1 Abstract

This paper provides a brief review of the most common statistical techniques for deterioration modeling of wastewater pipelines found in the published literature. An overview of wastewater pipelines condition assessment process and the characteristics of wastewater pipelines condition assessment data is also presented. A case study illustrates the potential pitfalls due to ignoring data type and modeling assumptions.

The wastewater collection network at the City of Niagara Falls is inspected using Side Scanner and Evaluation Technology (SSET) camera to develop a high quality wastewater pipelines condition assessment database. The SSET camera has demonstrated advantages over the traditional Closed Circuit Television (CCTV) cameras and is more accurate in depicting various defects in wastewater pipelines. To ensure high quality of the collected data, only certified and trained camera operators and personnel were allowed to collect and process data. Additional procedures are implemented in the database to import only the validated data. The common state-of-the art statistical methodologies for deterioration of wastewater pipelines, such as expected value and binary logistic regression, are applied to develop deterioration models and check model assumptions and other characteristics. Additionally, the wastewater pipelines deterioration models based on expert judgment, ordered probit regression and Markov chains are discussed.

It is found that the existing deterioration models for wastewater pipelines have one or more of the following limitations: (1) they violate model assumptions or assumptions cannot be verified due to limited data; (2) they do not take into account the ordinal nature of response

data; (3) they are based on data obtained from third party sources with little or no quality assurance and quality control procedures in place; and (4) they are complex in terms of number of parameters to be estimated and interpreted.

The violation or failure to check model assumptions, and model complexity and limited interpretations can lead to poor data analysis and invalid results. The root cause of some of these limitations is the scarcity of good quality data on wastewater pipelines. A long-term wastewater pipelines performance research initiative is imperative to develop better understanding of their degradation behaviour. This will also help in intelligent decision making with respect to cost-effective maintenance, rehabilitation and replacement of wastewater collection systems.

4.2 Introduction

A critical element of urban infrastructure asset management process includes the development of reliable and useful deterioration models. The deterioration models are required to: (1) understand infrastructure degradation behaviour; (2) determine future infrastructure needs; (3) develop renovation and replacement plans; and (4) estimate assets' value, renovation and replacement costs, and user rates. The literature review revealed that the most commonly used techniques for wastewater pipelines deterioration modeling include: (1) expert judgment; (2) ordinary regression; (3) logistic regression; (4) ordinal probit regression; and (5) Markov chains. Ordinary regression based methodologies, such as expected value and non-linear optimization, and ordinal probit regression were employed to estimate transition probabilities in Markov chains models.

The following sections provide an overview of the traditional wastewater pipelines condition assessment process and discuss the salient features of wastewater pipelines condition assessment data. Furthermore, a review of the existing deterioration models for wastewater pipelines is presented and some of their limitations illustrated using a case study.

4.3 Wastewater Pipelines Condition Assessment

Wastewater pipelines condition assessment process generally involves: (1) visual inspection of pipes; (2) defects identification and classification; and (3) assigning a structural and operational condition grade depending upon type and severity of defects. It is noted that a number of wastewater pipelines' inspection technologies and condition assessment protocols have been developed in the last four decades, and are being used in the field.

4.3.1 Wastewater Pipelines Inspection Technologies

The inspection technologies are mostly classified as (Wirahadikusumah et al., 1998):

1. Visual Inspection Technologies
    i. Zoom Cameras
    ii. Closed-Circuit Television (CCTV) – Most commonly used around the globe.
    iii. Digital Scanners
        i. Side Scanner and Evaluation Technology (SSET)
        ii. Flash Cameras
2. Laser Profilers
3. Remote-Sensing Diagnostic Techniques – Include Infrared Thermography System, Ground Penetration Radar (GPR) System, Sonic Distance Measurement Method.
4. Multi-Sensory Systems – Include KARO and PIRAT.

Wirahadikusumah et al. (1998) discussed advantages and limitations of above mentioned inspections technologies. Remote-sensing and multi-sensory techniques are still not very common, and efforts continue to modify, enhance, and improve them for usage in wastewater collection systems. Remotely controlled Closed Circuit Television (CCTV) and more recently Side Scanning Evaluation Technology (SSET) cameras also known as Sewer Scanner and Evaluation Technology are most commonly used for visual inspections of interior of wastewater pipelines. Pipeline inspections are completed by an operator remotely moving the camera down the pipeline and coding all observed defects using a defect condition coding system.

The SSET inspection cameras have demonstrated advantages over CCTV cameras. The Civil Engineering Research Foundation (CERF) carried out field evaluation of SSET and compared SSET with CCTV. CERF (2001) concluded that: (1) SSET provided “significant enhancements” as compared to CCTV; and (2) SSET accurately depicted the type and size of various defects, such as cracks, fractures, breaks, debris, and open and displaced joints. Some of the SSET limitations included poor performance in dark colored pipes and inability to provide information about infiltration and inside of laterals (CERF, 2001).

4.3.2 Wastewater Pipelines Defects Identification and Classification

There are hundreds of different defect code sets and condition assessment protocols used by various utilities, consulting engineers, vendors, and contractors (Rahman et al., 2004; NASSCO, 2006). However, WRc’s (Water Research centre, UK) condition assessment protocol as detailed in the Manual of Sewer Condition Classification (WRc, 1993) and Sewerage Rehabilitation Manual (WRc, 2001) has been adopted worldwide as the industry standard for assessment and renewal of wastewater infrastructure.

In North America, two predominantly used defects classification systems include: (1) the WRc’s 3rd edition of the MSCC (Manual of Sewer Condition Classification); and (2) PACP (Pipeline Assessment and Certification Program) developed by NASSCO (National Association of Sewer Service Companies) with the help of WRc.

The Manual of Sewer Condition Classification, first published in 1980, became the national standard in UK and many other parts of the world. WRc published the 3rd and 4th edition of MSCC in 1994 and 2004, respectively. In 1994, the North American Association of Pipeline Inspectors (NAAPI) adopted WRc's MSCC 3rd edition and developed a certification program for CCTV operators and reviewers – the first of this kind in North America until 2002. PACP was published by NASSCO in 2002 to meet the needs of the wastewater pipelines inspection industry in the USA.

4.3.3 Wastewater Pipelines Condition Grading

The WRc's Sewerage Rehabilitation Manual (SRM) describes a wastewater pipelines condition grading and renovation decision making process which has been adopted in the United Kingdom and Canada. The first edition of the SRM was published in 1986 and the current fourth edition was published in 2001. The SRM describes the structural and operational performance of wastewater pipelines by assigning scores to MSCC defects based on their type and severity. The structural defect scores are transformed – based on pipeline's peak defect score (refer to Table 4.1) – to Structural Internal Condition Grade (ICG) of 1 to 5, with 1 being the best or acceptable and 5 being the worst or near collapsed state.

Table 4.2 shows the structural ICG and their implications suggested by WRc (WRc, 2001). The continued use of the SRM methodology, in United Kingdom and Canada since 1994, validates the methodology as an acceptable and good approach for determining pipeline current condition states. The general principles of the SRM also form the basis for the

European Standard EN752-5 – Drain and Sewer Systems Outside Buildings: Part 5 Rehabilitation. This further validates the SRM approach.

Table 4.1: Structural Internal Condition Grading (WRc, 2001)

Internal Condition Grade (ICG)	Peak Score
1	< 10
2	10 – 39
3	40 – 79
4	80 – 164
5	≥ 165

NASSCO's PACP manual contains a pipeline condition rating scheme that varies from 1 to 5. The PACP condition rating depends on average score (total defects score divided by the number of defects) rather than peak score as used by the WRc. Unlike WRc's SRM, the PACP manual has no detailed decision making process. Presently, limited published data exists to validate the PACP defect scores rating system in North America. According to Stantec (2009), usage of average scores instead of peak scores for condition rating is a limiting issue of PACP methodology. PACP methodology, therefore, may not be able to accurately prioritize rehabilitation needs of wastewater collection systems (Stantec, 2009).

Table 4.2: Internal Condition Grades (WRc, 2001)

Grade	**Implication**
5	Collapsed or collapse imminent
4	Collapse likely in foreseeable future
3	Collapse unlikely in near future but further deterioration likely
2	Minimal collapse likelihood in short term but potential for further deterioration
1	Accepted structural condition

4.4 Wastewater Pipelines Condition Assessment Data

Majority of the utilities and municipalities do not perform regular inspections and have incomplete system inventories. In 2004, the Ministry of Finance in Ontario, Canada, completed a survey (PricewaterhouseCoopers, 2003) to investigate municipal water and wastewater systems asset management practices in Canada. This survey found that 52% of all the responding municipalities do not either perform asset inspections or record information regarding the performance of their systems. Therefore, the lack of good quality data is a major problem in developing reliable and useful deterioration models for wastewater pipelines, and has been documented in the published literature (see for example, Baik et al., 2006; Wirahadikusumah et al., 2001).

Characteristics of Wastewater Pipelines Condition Assessment Data

The deterioration may be intrinsically continuous, however, for wastewater pipelines it is mostly measured in discrete and ordinal – that is, non-continuous – Structural Internal Condition Grades (ICG) or Structural Performance Grades (SPG). WRc's ICG were developed as distinct condition grades as shown in Figure 4.1 (hypothetical illustration). A pipeline remains in a condition grade until a point in time when it meets the requirement to move into the next condition grade. For example, the pipeline in Figure 4.1 remains in ICG 1 from installation to 21 years, and at age 21.1 years it jumps immediately into ICG 2.

Thus, the condition of wastewater pipelines is measured on a categorical scale. The pipelines internal condition grades, therefore, represent categorical/discrete responses as opposed to continuous response. The categorical response variables may be of *nominal*, *ordinal*, or *interval* types depending upon how they are measured (Agresti, 2002). The distinction between nominal, ordinal, and interval data types is given below.

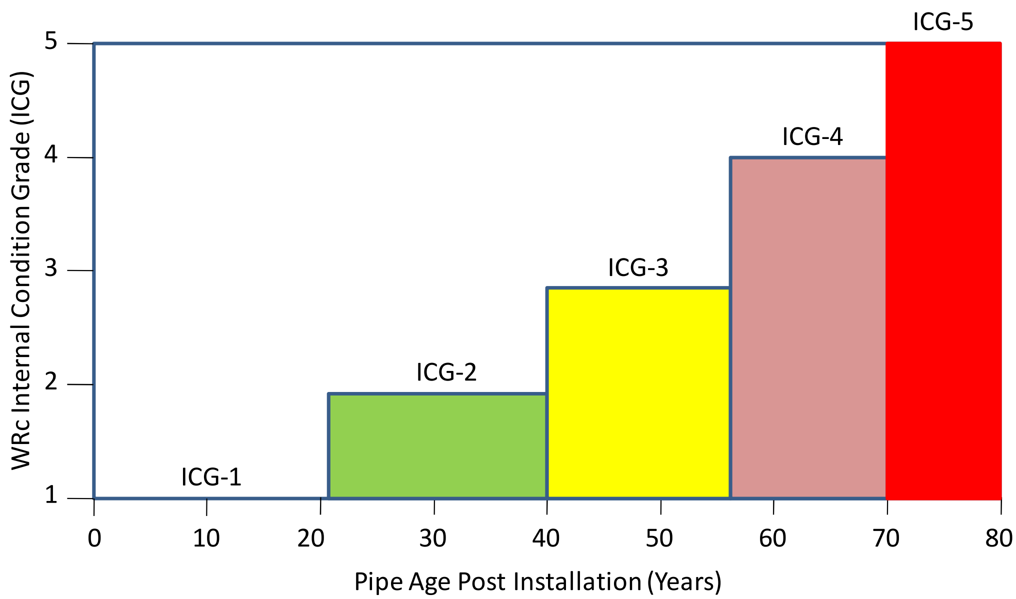

Figure 4.1: Hypothetical Deterioration Phenomenon using WRc's ICG

Nominal Variables are qualitative variables, and have categories with no natural ordering. The variable '*pipe_material'*, for example, is a nominal variable that can take values such as reinforced concrete and vitrified clay.

Ordinal Variables have ordered categories, but the distance between categories is unknown. They can be qualitative or quantitative. For example, wastewater pipelines internal condition grade is an ordinal variable (refer to Table 4.2).

Interval Variables have ordered categories and defined numerical distances between the categories. They are essentially quantitative variables.

Statistical methods may depend on how categorical responses are measured. Agresti (2002) noted, "in the measurement hierarchy, interval variables are the highest, ordinal variables are next, and nominal variables are the lowest … the statistical methods suitable for lower variable types can be used for higher variables, but not vice versa." Therefore, type of response and explanatory data should be considered in statistical modeling.

4.5 State-of-the-Art Deterioration Models

Ordinary Regression, Expected Value and Non-Linear Optimization

Fick et al. (1993) regressed *condition scores* with *age* for various pipe materials. Baik et al. (2006); Wirahadikusumah et al. (1999); Wirahadikusumah et al. (2001); and Wirahadikusumah and Abraham (2003) used *expected value* and *non-linear optimization* approaches to compute transition probabilities for Markov chains based deterioration models for wastewater pipelines.

Binary Logistic Regression

Davies et al. (2001) and Ariaratnam et al. (2001) used binary logistic regression for modeling wastewater pipelines' deterioration. The response variable i.e., wastewater pipelines' condition grades were modeled as a binary/dichotomous variable that could take values either 1 or 0, corresponding to good/non-deficient or failed/deficient states, respectively. The pipelines condition grades 1, 2, 3, and 4 were coded using dummy variable '1' corresponding to good/non-deficient, and grade 5 was coded as '0' corresponding to failed/deficient state.

Expert Judgment

This approach relies on the judgment of an expert or a group of experts who based on their experience carry out a direct assessment of condition, and estimate the remaining life of an asset.

Kathula et al. (1999) proposed a Sanitary Sewer Management System (SSMS) based on experts' opinion. Kathula et al. (1999) devised a survey whereby condition of a pipe was described to sewer experts through words and pictures. The experts were shown pictures of pipes in various conditions, and were asked to guess the probability that sewer pipes' condition would change from current to a more severe condition during five year period. Typically, two pictures were printed side-by-side, and the question asked, "out of 100 pipes, how many pipes will go from the condition shown in the left picture to the condition shown in the right picture during the five year period" (Kathula et al., 1999). Based on 55 responses, mean values of probabilities of sewer pipes moving from a particular condition to a more severe condition were calculated.

Kathula et al. (1999), based on the survey responses, developed a number of curves showing the percentage of pipes going through different states over 50 years of period.

Stevenson and Macey (2005), in the Life-Cycle State of Infrastructure Report on Public Works Assets for the city of Hamilton, Ontario, Canada, used a simplified deterioration curve as shown in Figure 4.2. They asked the asset managers to mark the current physical condition of assets to the best of their knowledge on the curve. Stevenson and Macey (2005), based on a hypothetical life of 80 to 100 years, assumed that 5% of assets would fail in 50% of asset life, 15% would fail in 75% of asset life, 65% would fail in 125% of asset life , while the remaining would fail at 100% of asset life.

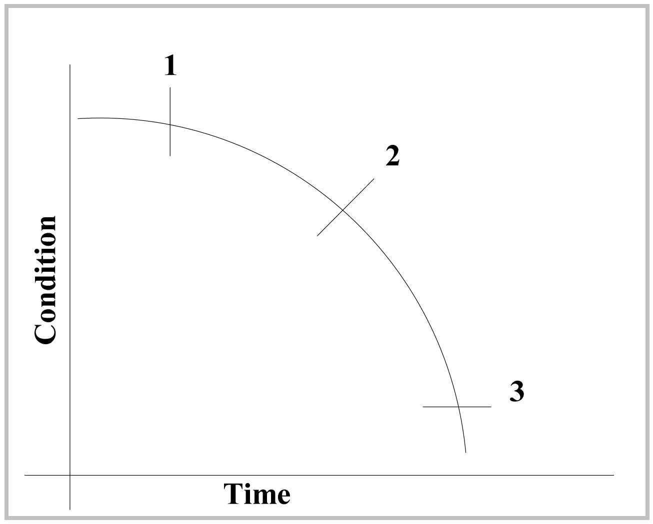

Figure 4.2: Simplified Deterioration Curve (Stevenson and Macey, 2005)

Markov Chains and Ordered Probit Models

In a Markov model the probability of jumping into a state at time $t+1$ depends only on the state occupied at time t, and is independent of the history of the process up to time t (Hillier and Lieberman, 1980). Baik (2003); Baik et al. (2006); Burgess (1990); Jeong et al. (2005); Kathula et al. (1999); Micevski et al. (2002); Wirahadikusumah et al. (1999); and Wirahadikusumah and Abraham (2003) used Markov chains models for the deterioration of wastewater pipelines. Expected value (non-linear optimization) and/or ordered probit regression were used to estimate transition probabilities. Baik (2003); Baik et al. (2006); and Jeong et al. (2005) used ordered probit regression to estimate probabilities, and employed these probabilities as the transition probabilities in Markov chains models for sewers deterioration.

4.6 Case Study

This section presents the application of ordinary and binary logistic regression models to the wastewater pipelines condition assessment data collected from the City of Niagara Falls. Furthermore, deterioration models based on expert judgment, ordinal probit regression and Markov chains are discussed.

4.6.1 City of Niagara Falls Wastewater Pipelines Condition Assessment Data

To ensure that a high quality SSET pipeline condition assessment database is developed for the City of Niagara Falls wastewater network, the data collection and data analysis procedure, shown in Figure 4.3, was implemented. A contractor supplied North American Association of Pipelines Inspectors (NAAPI) certified operator completed all the SSET pipeline surveys, and coded all pipeline defects in accordance with the Manual of Sewer Condition Classification 3rd edition (WRc, 1993). Using NAAPI certified City of Niagara Falls personnel, a second Quality Assurance (QA) and Quality Control (QC) check was performed on all the contractor provided data.

All of the City of Niagara Falls quality pipeline inspection data was transported to the University of Waterloo to be stored on two geographically distributed data servers that are backed up using RAID 5 technology to ensure data security, availability, and seamless recovery. Using a University of Waterloo custom built software application, the City of Niagara Falls QA/QC data is uploaded into a database management system named WatBAMS (Waterloo – Buried Asset Management System). The software import utility contains further QA/QC protocols to ensure that only high quality data is uploaded in the

WatBAMS database for each pipe segment survey. Using WatBAMS programmed routines, each pipeline segment is analyzed in accordance with the Sewerage Rehabilitation Manual 4^{th} edition methodology to determine the corresponding Internal Condition Grade (ICG). WatBAMS also allows for the upload and integration with the City's of Niagara Falls GIS and inventory databases that contain each pipe segment's attributes - asset ID, location, construction date, and material type etc.

The City of Niagara Falls wastewater collection network consists of approximately 400 km of pipelines that has approximately 5,500 pipe segments consisting of a variety of pipe materials with ages that range from over 100 years to less than 20 years with an average age of 47 years. It is noted that that 35% of the network consists of Reinforced Concrete (RC), 17% PVC, 10% Vitrified Clay (VC), 10% Asbestos Cement (AC), and 25% of the network has no assigned pipe material. The average age of the RC and VC pipes are 42 and 65 years, respectively. Review of the SSET surveys and defect reports found that VC pipes have open and displaced joints and service connections that were installed by creating a hole in the clay pipe. Thus, there are holes and cracks where service connections enter into the VC pipes. RC pipes were found to be generally in good condition except for locations with few displaced joints and structural defects such as cracks, fractures, and broken segments. None of the pipes in the sample were rehabilitated or replaced, and therefore, none of the observations were censored. Approximately 12% (45 km) of the City of Niagara Falls wastewater collection network data is used in the development of ordinary and binary logistic regression models.

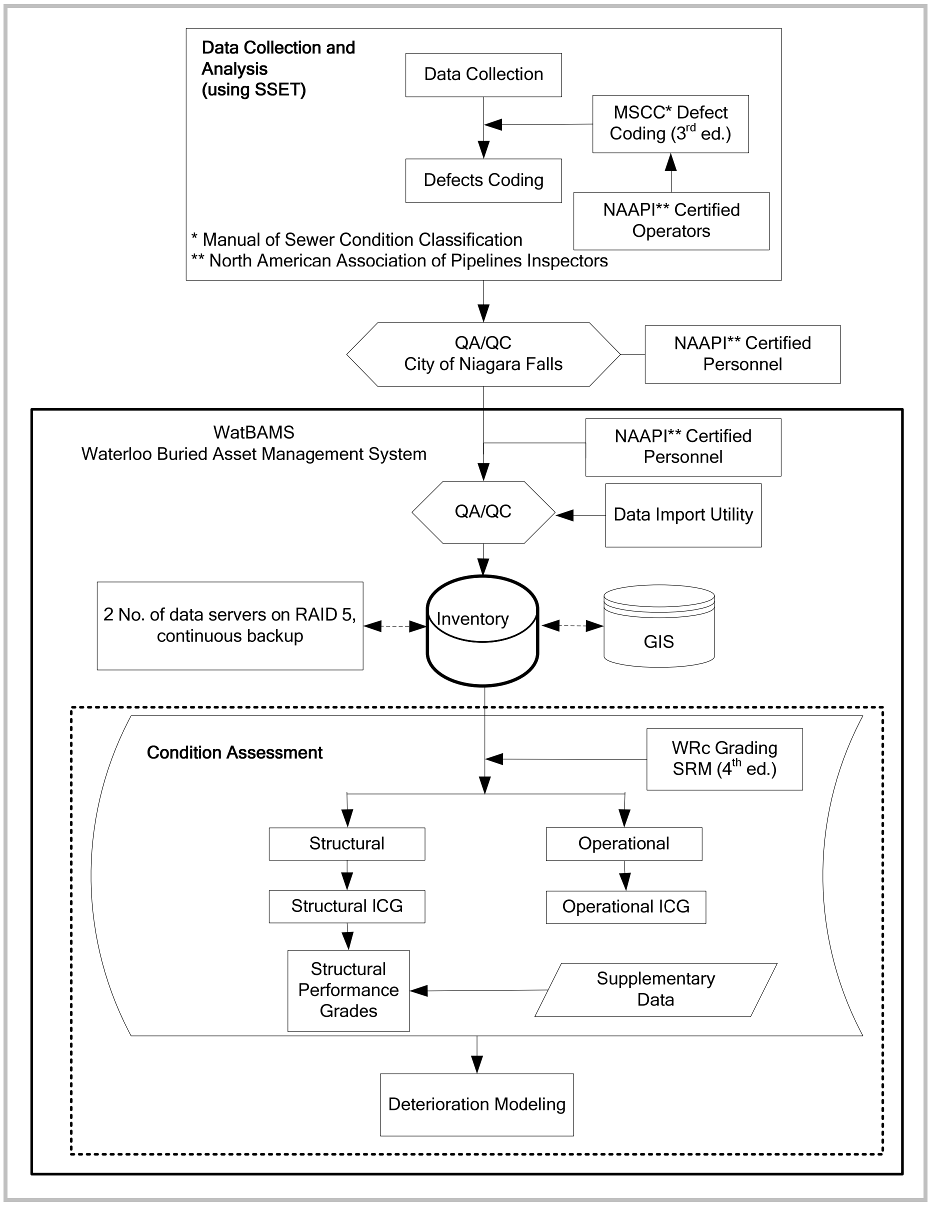

Figure 4.3: Data Collection and Deterioration Modeling Framework

4.6.2 Application and Discussion of Existing Models

Ordinary Regression, Expected Value and Non-Linear Optimization Based Methodologies

It is noted that the *expected value methodology* is essentially ordinary least square (OLS) regression (linear or non-linear) where *condition grades* of wastewater pipelines are regressed on *age*. The distance between expected value of condition rating and the average condition rating at time t is minimized using non-linear optimization.

Hoffmann (2004) and Pampel (2000) discussed the limitations of ordinary regression to model binary and ordinal data. Madanat and Wan Ibrahim (1995); Madanat et al. (1995); and Mishalani and Madanat (2002) criticized the application of expected value and non-linear optimization techniques in transportation assets (e.g., pavements and bridges) deterioration modeling. Wirahadikusumah et al. (2001) and Wirahadikusumah and Abraham (2003) pointed to the limitations of expected value and non-linear optimization methodologies for wastewater pipelines deterioration modeling and cited the scarcity of data in developing better models.

The ordinary regression based methodologies are not suitable for modeling the degradation of wastewater pipelines for the following reasons:

1. Ordinary regression assumes that the distance between adjacent categories (condition grades) is constant. However, it is important to note that there is no underlying interval scale between the wastewater Internal Condition Grades (ICG), i.e., $ICG\ 2 - ICG\ 1 \neq ICG\ 3 - ICG\ 2$.

2. Figure 4.4 shows the scatter plot of *ICG* vs. *Age* for the wastewater pipelines condition assessment data from the city of Niagara Falls. All the observations are nicely lined up corresponding to the internal condition grades. The regression curve clearly shows that the assumption of homoscedasticity – that is, constant variance of error term – is violated.

This results in biased standard errors of estimated coefficients which lead to incorrect significance tests and probably wrong inferences.

3. Ordinary regression assumes normally distributed error term which is an important assumption for making inferences. However, this assumption is usually violated when ordinary regression is used to model ordinal response variables. To further clarify this issue, a quadratic regression model is applied to a sample of condition assessment data of wastewater pipelines. The results are presented in Figures 4.4 and 4.5. Figure 4.4 shows heteroscedasticity problem when a quadratic regression line is fitted to the data. Figure 4.5 shows the normal probability plot to verify the assumption of normally distributed error terms. The snaking pattern of residuals indicates that they are not normally distributed.

4. The predicted values of dependent variable may be higher than the possible values of the dependent variable in case of an ordinary regression model.

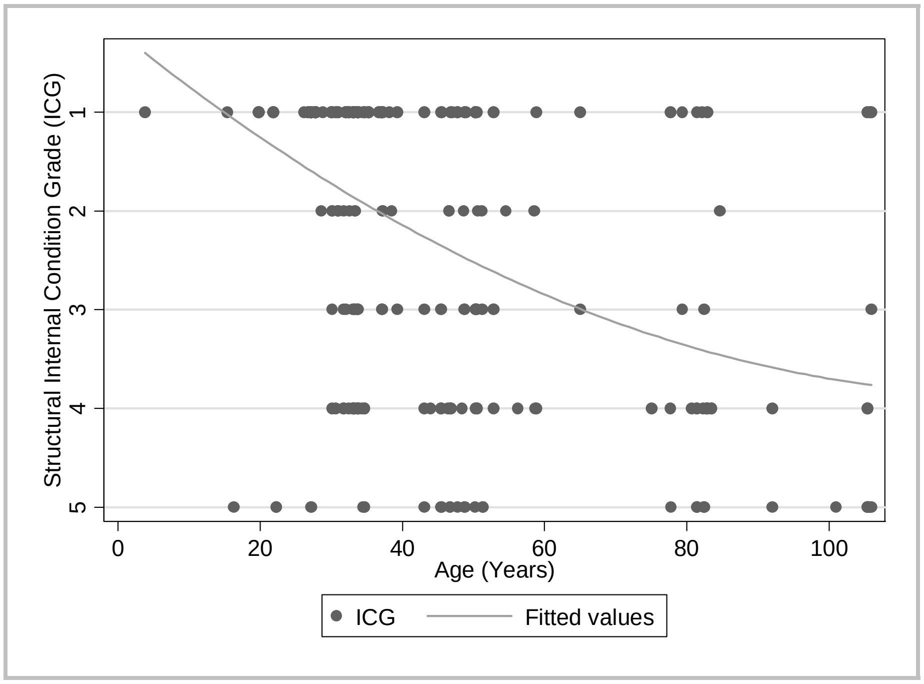

Figure 4.4: Scatter Plot of *ICG* and *Age* and a Quadratic Regression Line

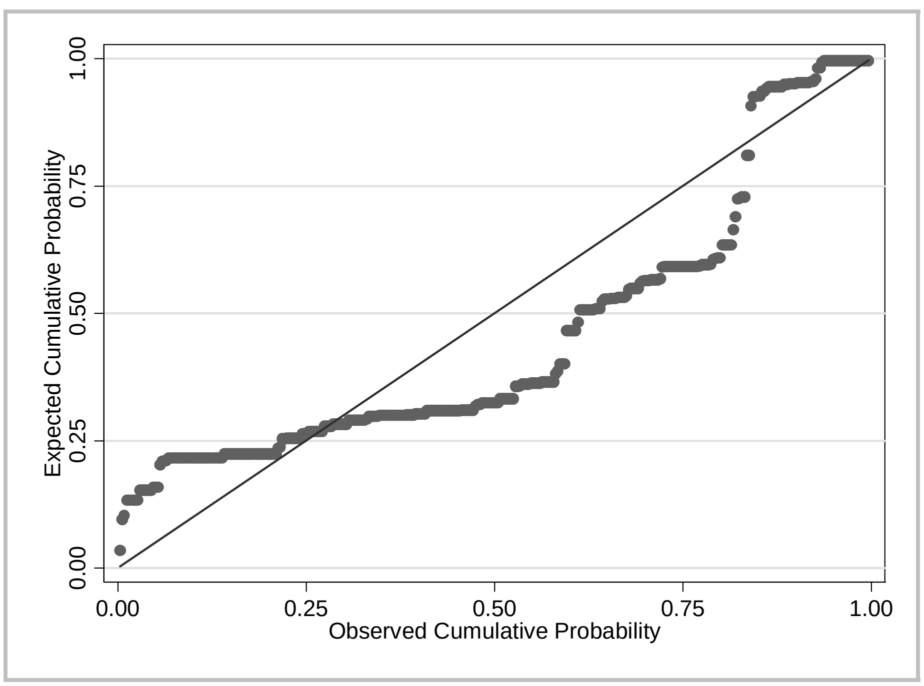

Figure 4.5: Normal Probability Plot of Residuals (from the model shown in Figure 4.4)

Binary Logistic Regression

This methodology is limited in scope and usefulness to model data with more than two categories. According to Agresti (1996), “it is usually *inadvisable* [italics added] to collapse ordinal data to binary.” Collapsing five condition grades into two – that is, into pass and fail categories – throws away additional information contained in the data. This is illustrated by applying the binary logistic regression and ordinal logit models to the City of Niagara Falls wastewater pipelines condition data. To obtain binary logistic model, the condition grades 1 to 4 are collapsed and termed as *pass* whereas grade 5 is termed as *fail* grade. The ordinal logit model extends the binary logit model when the response variable has more than two ordered categories. The detailed information about ordinal logit model development and application is provided in Chapter 5. Table 4.3 shows the parameter estimates for binary logistic and ordinal logit models. The standard deviations (Std. Err.) in case of binary logistic model are larger as compared to the ordinal logit model. For example, the Std. Err. for *material* predictor is 0.9808 in binary logistic model as compared to 0.6330 in ordinal logit model as shown in Table 4.3. This shows that collapsing condition grades results in loss of information.

Table 4.3: Parameter Estimates for Binary Logistic and Ordinal Logit Regression Models

Parameter	**Binary Logistic Regression**		**Ordinal Logit Model**	
	Coefficient	Std. Err.	Coefficient	Std. Err.
Age	0.0076	0.0075	0.0084	0.0069
Material	-4.6252	0.9808	-3.4391	0.6330
$Age \times Material$	0.0583	0.0155	0.0462	0.0110

Expert Judgment

Expert probability estimates, while commonly used in decision analysis when data is not available or knowledge is vague, can be highly inaccurate. In Civil engineering applications, field conditions introduce uncertainty in the application of expert knowledge. Meyer and Booker (1991) referred to some case studies that reported human biases in probability estimates. It is generally observed that experts are not good estimators of probability values and predictions. Asking experts to assign probability values to predict the likelihood of occurrence of some event or to comment on the condition of an asset without inspection is too much to ask. According to Morgan (1990), "elicited expert subjective judgment is *no substitute* [italics added] for proper scientific research," and "can reduce pressures to obtain research output, and thus result in diminished investments in needed research."

Markov Chain and Ordered Probit Regression Based Methodologies

To use Markov chains for deterioration modeling of wastewater pipelines, assumptions about *homogeneity* and *order* were employed but could not be verified. According to Lindsey (2004), sufficient number of replicate series is required to test homogeneity, and details of changes for each series for at least three consecutive time periods are required to examine the order. It is not plausible to assume that the assumptions hold *a priori,* and is important to test that the assumptions of Markov chains are "at least approximately" reasonable (Lindsey, 2004). It is noted that in the absence of longitudinal condition assessment data – that is, repeated observations on same samples – researchers used ordinary or ordered probit regression to determine transition probabilities for Markov chain models. Lindsey (2004) noted, "marginal probabilities describe the underlying trend of the process, and do not uniquely define a stochastic process." It is difficult to authenticate the results of Markov chain based deterioration models due to data limitations.

The Markov chains model proposed by Micevski et al. (2002) for the deterioration of storm water pipelines is a multinomial model which does not take into account the ordinal nature of response variable. The ordered probit model used in the study by Baik et al. (2006) did not fit the data well. Baik cited the poor quality of data as one of the possible reasons for the lack of model fit. The ordered probit models found in the literature are complex – that is, they are fully unconstrained – in terms of number of parameters to be estimated. This makes their interpretation very difficult. Furthermore, the interactions between important covariates such as *age* and *material* are not taken into account.

4.7 Discussion and Conclusions

This paper provided an overview of wastewater pipelines condition assessment and state-of-the-art deterioration modeling techniques. Some of the limitations of existing deterioration models are illustrated by applying these models to the pipelines condition assessment data collected by the author from the City of Niagara Falls wastewater collection system.

Remote controlled Closed Circuit Television cameras and more recently Side Scanning and Evaluation Technology cameras are widely used for wastewater pipelines inspection surveys. Water Research centre (WRc) protocols were found to be widely accepted and used for defect coding, classification, and condition assessment of wastewater pipelines. The most commonly used statistical deterioration modeling techniques for wastewater pipelines included: expert judgment, ordinary regression, binary logistic regression, and Markov chains based models. The transition probabilities in Markov chains were estimated using ordinary regression based methodologies (e.g., expected value or non-linear optimization) or ordered probit regression.

Expert judgments suffer from serious limitations and problems, such as, data validity, scientific justification, and calibration. Follow up research need to be conducted to validate and justify the initial elicited inferences. Ordinary regression – when applied to the wastewater pipelines condition data collected by the author – violated normality assumption as well as suffered from heteroscedasticity problem. These problems result in incorrect statistical tests for parameters and biased confidence intervals. Using binary logistic regression by collapsing multi-category ordinal response data into binary response resulted in loss of information. Suitable data does not exist to verify the assumptions of Markov chain based deterioration models for wastewater collection systems. Ordered probit regression models contained too many parameters, and thus made their interpretations extremely difficult. To summarize, the most common concerns with the existing wastewater deterioration models include one or more of the following:

(1) they violate the model assumptions or assumptions are not verified;

(2) they do not take into account the ordinal nature of the data;

(3) they are based on data obtained from third party sources with little or no information about data quality assurance and quality control procedures; and

(4) they are complex in terms of number of parameters to be estimated which can lead to invalid interpretations.

Lack of adequate condition assessment data impedes progress in understanding the deterioration behaviour of wastewater pipelines. It is high time that utility owners must commit to the development of new high quality inspection databases. Reliable and useful deterioration models will help by improving decision-making and developing cost-effective maintenance, management and renovation/replacement programs for wastewater infrastructure.

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Chapter 5

A Probability Model for Investigating the Trend of Structural Deterioration of Wastewater Pipelines

This paper has been submitted to the Tunneling and Underground Space Technology journal.

5.1 Abstract

Canada's infrastructure is aging and deteriorating. New legislation requires the municipalities to estimate operating and capital expenditures for running the systems into the future and to develop financial sustainability plans. Wastewater pipelines deterioration is currently not well understood and realistic deterioration models need to be developed.

This paper demonstrates how the condition assessment data from trenchless visual inspections of wastewater pipelines can be used to understand the performance of wastewater pipelines. A new ordinal regression model for the deterioration of wastewater pipelines based on cumulative logits is elaborated. The model is presented using the Generalized Linear model formulation and takes into account the interaction effect between the explanatory variables. The new model is demonstrated and validated using the City of Niagara Falls high quality wastewater collection network condition assessment data for Reinforced Concrete (RC) and Vitrified Clay (VC) pipes.

This new model was found to represent the City of Niagara Falls RC and VC pipes deterioration behavior for pipes in service for up to 110 years. RC pipes deterioration was found to be age dependent while VC pipes deterioration was not age dependent. This finding is contrary to other deterioration model studies that indicate that VC deterioration is age dependent. The service life for RC pipes was determined to be approximately 75 years while VC pipes were found to have an indefinite service life if installed without structural damage.

The cumulative logit model can be used to determine wastewater pipelines service life, predict future condition states, and estimate network maintenance and rehabilitation expenditures. The latter is critical if realistic wastewater networks future maintenance and operation budgets are to be developed for the life of the asset, and to meet new regulatory reporting requirements. Further research is required to validate this new methodology for other networks and the deterioration modeling of pipe materials other than RC and VC.

Keywords: Wastewater pipelines; Deterioration modeling; Statistical modeling; Asset management; Vitrified clay pipes; Reinforced concrete pipes

5.2 Introduction

A large percentage of Canada's buried municipal water and wastewater piping networks have exceeded or are approaching its design life of 50 to 75 years. Therefore, this aging and deteriorating infrastructure needs to be renewed or replaced. Estimates of Canada's municipal infrastructure deficit vary from a $44 billion total municipal infrastructure shortfall (TD Economics, 2002) to over $125 billion (Mirza, 2007). The municipal infrastructure deficit is an estimate of the total additional investment needed to repair and prevent deterioration in existing, municipally owned infrastructure assets. Mirza (2007) reports that the infrastructure funding gap for existing water and wastewater is $31 billion, and to meet new needs an additional $56.6 billion is required. The size and scope of the infrastructure problems facing municipalities and local governments is enormous as the decay of Canada's infrastructure creates severe domino effects - higher cost of maintenance, operation, rehabilitation and repair; inefficiency and increased vulnerability; and increased threats to public safety and the environment. Mirza (2007) states that "without maintenance or with deferred maintenance, the municipal infrastructure deficit could be close to $2 trillion by 2065 and that with regular maintenance and good scientific management, the escalating infrastructure deterioration and the resulting infrastructure deficit can be controlled within manageable levels."

In 2006, the Canadian Institute of Chartered Accountants Public Sector Accounting Board (PSAB) issued statement PS3150 which requires all Canadian municipalities and utilities, starting in January 2009, to report their tangible capital assets along with their depreciation on financial statements (OMBI, 2007). One of PSAB requirements is the estimation of operating and capital expenditures for running the systems into the future. In the United States, the Governmental Accounting Standards Board (GASB) Statement 34, and in Australia, the Australian Accounting Research Foundation Standard 27 (see FHWA, 2000; Howard, 2001) specify similar accounting practices. To meet these specified accounting practices, knowledge on how the assets behave and deteriorate over time is imperative.

Current Canadian government guidelines suggest that the useful life for various civil infrastructure assets and for wastewater pipelines range from 40 to 75 years (Ministry of the Environment, 2007; NAMS, 2002) with limited or no asset deterioration knowledge. The absence of asset deterioration knowledge necessitates Canadian municipalities to make unsubstantiated assumptions about the timing and volume of capital expenditures so that they can comply with PSAB and other government and regulatory requirements. These unsubstantiated assumptions will most likely result in an under or over-estimation of assets future operational and capital needs. To develop realistic future life-cycle asset operation and maintenance financial needs it is imperative that asset deterioration behavior is understood and realistic deterioration models are developed and used for future predictions.

This paper provides an overview of trenchless wastewater condition assessment methodology and protocols. It also discusses ordinal regression models and their applications in civil engineering. An ordinal regression model, based on cumulative logits, is developed and described along with its assumptions and the estimation procedure for predicting wastewater infrastructure deterioration. The new deterioration model is demonstrated using City of

Niagara Falls wastewater collection system pipeline condition assessment data, and procedures for verification of assumptions, determination of parameter estimates, validation, and model interpretation are presented. The paper concludes with a discussion on the results, and deterioration model limitations.

5.3 Literature Review

A review of current industry practices with respect to wastewater pipelines condition assessment and deterioration modeling using ordinal regression models is provided in the following sections.

5.3.1 Condition Assessment of Wastewater Pipelines

Assessment of current condition of wastewater pipelines is an important component of buried infrastructure management processes. Trenchless condition assessment technologies such as remotely controlled Closed Circuit Television (CCTV) and more recently Side Scanning Evaluation Technology (SSET) cameras also known as Sewer Scanner and Evaluation Technology are used for visual inspections of interior of wastewater pipelines. Information provided by these cameras is critical to determine if and what trenchless construction methods can be used to repair, renovate or replace deteriorated buried pipelines. The development of realistic pipe deterioration models is also necessary for advanced buried infrastructure asset management- that is, to fix the right asset at the right time to optimize the limited resources. Pipeline inspections are completed by an operator remotely moving the camera down the pipeline and coding all observed defects using a defect condition coding system. In North America, two wastewater pipeline defect condition Classification systems are predominately used: (1) Manual of Sewer Condition Classification (MSCC) 3rd edition defect coding system developed by Water Research Center (WRc) in the United Kingdom (WRc, 1993); and (2) Pipeline Assessment and Certification Program (PACP) developed by National Association of Sewer Service Companies (NASSCO) and WRc (NASSCO, 2006; Thornhill, 2005).

The Manual of Sewer Condition Classification, first published in 1980, became the national standard in UK and many other parts of the world. In 1994 and 2004, the 3rd and 4th editions of MSCC were published by WRc, respectively. In 1994, the North American Association of Pipeline Inspectors (NAAPI) adopted WRc's MSCC 3rd edition and developed a Certification program for CCTV operators and reviewers. In 2002 NASSCO published PACP to meet the needs of the United States. The Sewerage Rehabilitation Manual (SRM), also published by WRc, describes a wastewater pipelines renovation decision making process that is adopted in the United Kingdom and Canada. The first edition of the SRM was published in 1986 and the fourth edition was published in 2001 (WRc, 2001). The SRM determines the structural and operational performance of wastewater pipelines by assigning scores to MSCC defects based on their type and severity. These scores are transformed to Internal Condition Grade (ICG) of 1 to 5, with 1 being the best or acceptable and 5 being the worst or collapsed state. The continued use of the SRM methodology, in United Kingdom and Canada since 1994, validates the methodology as an acceptable and good approach for determining pipeline current condition states. The general principles of the SRM also form the basis for the European Standard EN752-5 – Drain and Sewer Systems Outside Buildings: Part 5 Rehabilitation. This further validates the SRM approach. NASSCO's PACP manual contains a pipeline condition rating scheme that varies from 1 to 5. The PACP condition rating depends on average score (total defects score divided by the number of defects) rather than peak score as used by the WRc. Unlike WRc's SRM, the PACP manual has no detailed decision making process. Presently, limited published data exists to validate the PACP defect scores rating system in North America. According to Stantec (2009), usage of average scores instead of peak scores for condition rating is a limiting issue of PACP methodology. PACP methodology, therefore, may not be able to accurately prioritize rehabilitation needs of wastewater collection systems (Stantec, 2009).

In 2004, the Ministry of Finance in Ontario, Canada, completed a survey (PricewaterhouseCoopers, 2003) to investigate municipal water and wastewater systems asset management practices. This survey found that among the responding Ontario municipalities, 17% do not perform inspections for condition assessment, and of those who do perform inspections, 33% do not record the results of the inspections. The survey also found that large municipalities (more than 50,000 populations) typically have better asset management practices and that asset management approaches range from "don't fix it if it is not broken" strategies to the use of computationally intensive and sophisticated software tools. This survey demonstrates the current state-of-art in asset management by municipalities in Canada and most likely in North America.

5.3.2 Ordinal Regression Models

Ordinal variables are a type of categorical variables that have natural ordering of categories, however, the distances between the categories is not known (Agresti, 2002). Ordinal regression models are extensively used in social and life sciences for analyzing data where response variable is rank-ordered or ordinal. These models are extensions of binary logit and probit models to polytomous response cases and are generally referred to as econometric models in civil engineering published literature. The difference between logit and probit models is in the distribution of error terms. In case of probit models, the errors are normally distributed, whereas in case of logit models, the errors are logistically distributed. Agresti (2002) and Nelder and McCullah (1989) provide extensive details of these models. Clogg and Shihadeh (1994) discusses a variety of ways of forming *"response functions"* for ordinal data which result in the development of different ordinal logit models.

To date, the application of ordinal regression models to solve civil engineering problems is limited although the data encountered is predominantly rank-ordered. For example, FHWA (1995) specifies ten condition grades from 0 (failed condition) to 9 (excellent condition) for condition ratings of bridge decks, and super and sub-structures. Similarly, Pavement Condition Index (a value between 0-100 based on multiple pavement distress indicators) is often discretized into eight rank-ordered categories from 1 representing failed to 8 representing excellent state (Madanat et al., 1995). Baik (2003) reviewed the application of ordinal regression models for civil infrastructure deterioration and found that ordered probit models were used for modeling the deterioration of pavement and bridges. Madanat et al.

(1995) and Baik et al. (2006) also used ordered probit models to model the deterioration of bridges and wastewater pipelines, respectively.

5.4 Problem Statement and Proposed Model Review

5.4.1 Problem Description

The numerical value of Internal Condition Grades (ICG) of wastewater pipelines is arbitrary. Therefore, instead of predicting an arbitrary value, the problem is restated as *predicting the probability of a wastewater pipeline being into one of the five condition grades as opposed to the others depending upon covariates such as pipe age and material*.

Davies et al. (2001) reported that concrete sewers are more likely to be in a lower ICG (more structurally sound) than clay sewers. They also suggest that this finding may be the result of clay pipes being significantly older than concrete pipes in the tested sample. This paper investigates the hypothesis that *vitrified clay pipes are more likely to be in a higher ICG (poor structural condition) than reinforced concrete pipes.*

5.4.2 Model Description

The ordinal regression model with cumulative logits based on *Generalized Linear Model (GLM)* formulation is described below.

Let the index $j = 1, 2, ..., J$ represents J ordered responses for which a probability model based on cumulative probabilities can be defined as $P(Y = j \mid \mathrm{x})$. A regression model for ordinal response, Y, based on cumulative probabilities may be specified as (Agresti, 2002):

$$P(Y \le j \mid \mathrm{x}) = \pi(\mathrm{x}) = F(\mu_j - \beta_j' \mathrm{x}) \tag{5.1}$$

where, $F(.)$ represents the standard cumulative distribution function (cdf) which is *logistic* in this case, and μ_j represent the $(J-1)$ cutpoints (also known as thresholds) corresponding to the ordered categories of response variable. This is the Generalized Linear Model (GLM) formulation, provided F(.) is the inverse link function. The log-odds transformation known as *logit* is the inverse function for the standard logistic cdf. Equation 5.1 can be written as:

$$F^{-1}[\pi(\mathrm{x})] = \mathrm{logit}[P(Y \le j|\mathrm{x})] = \mu_j - \beta_j' \mathrm{x} \tag{5.2}$$

The ordered logit relation given in Equation 5.2 can be expressed in terms of cumulative probability as:

$$P(Y \le j|\mathrm{x}) = \frac{e^{\mu_j - \beta_j' \mathrm{x}}}{1 - e^{\mu_j - \beta_j' \mathrm{x}}} \tag{5.3}$$

Under this parameterization, a positive slope (i.e., $\beta > 0$) means that larger values of predictor 'x' are associated with higher levels of Y. That is, the probability of being in a higher order category increases with large values of 'x' when $\beta > 0$. For J ordinal dependent categories, there will be $(J-1)$ predictions for each cumulative probability across successive response categories. The final category will always have a cumulative probability equal to 1 because all the elements will be at or below the final category. The $(J-1)$ logits will have different thresholds μ_j for different response categories; however, β's may or may not be same across different categories. When β's are constrained across responses, a Proportional Odds model is obtained. On the other hand, when β's are allowed to vary across categories, an Unconstrained Cumulative Logit model is obtained. A Partial Proportional Odds model will have some constrained, as well as, unconstrained β's across response categories for one or more covariates. The Score or Wald Tests can be employed to verify the proportional odds assumption (Long, 1997).

5.4.3 Assumptions

There are two fundamental assumptions for ordinal regression analysis:

1. Continuous predictors are linearly related to the logits of response variable. If it is determined that they are not linear, then correct scale/parametric form of continuous variables must be determined. Bender and Grouven (1998) pointed out that this is the most fundamental requirement that should be checked even before starting an ordinal analysis.

2. The outcome variable must have rank ordering for every predictor (Boorah, 2001; Harrell, 2001). According to Long (1997), the mere fact that a response variable can be

written in an ordered fashion is not enough to apply ordinal techniques because a variable may be ordered or unordered under a given context.

5.4.4 Interaction

In case of multivariable analysis, the effect of an independent variable on dependent variable may differ depending on the value of a third variable. This is called *interaction*. For example, the effect of age on the probability of a pipeline being in a certain condition grade can vary with the pipe material type. To check this possibility, the interaction between pipe *age* and *material type* is added in the model by creating a higher order term resulting from the product of pipe *age* and pipe *material*, namely $age \times material$.

5.4.5 Estimation

Using Equation 5.2, the probability of being in a certain category $j = 1, 2, ..., J$ is given by the difference between cumulative probabilities, i.e.,:

$$P\left(Y = j \mid \mathrm{x}\right) = P\left(Y \leq j \mid \mathrm{x}\right) - P\left(Y \leq j - 1 \mid \mathrm{x}\right) \tag{5.4}$$

The likelihood function is given as:

$$L = \prod_{i=1}^{n} \prod_{j=1}^{J} P\left(Y = j \mid \mathrm{x}\right)^{c_{ij}} \tag{5.5}$$

where $c_{ij} = 1$ if $Y = j$, and 0 otherwise.

Thus, for each J, Equation 5.5 shows the product of all observations for which $Y = j$. The log-likelihood equation is then given as:

$$\log L = \sum_{i=1}^{n}\sum_{j=1}^{n} c_{ij} \log\left[F\left(\mu_j - \beta_j \mathrm{x}\right) - F\left(\mu_{j-1} - \beta_j \mathrm{x}\right)\right] \tag{5.6}$$

Newton-Raphson or Fisher Scoring algorithms are employed to compute maximum likelihood estimates for model parameters β_j and μ_j.

5.4.6 Model Validation

Model validation and justification entails the following steps:

(1) *Checking fundamental assumptions for ordinal regression analysis i.e., linearity and ordinality assumptions*

Quartiles (or deciles) and Fractional Polynomial analyses can be performed to check the linearity of continuous predictors with the logit (Royston and Altman, 1994; Bender 1998; Hosmer 2002). To verify the ordinality of response variable, a simple graphical technique proposed by Harrell (2001) can be used. It involves the plot of mean values of a predictor within each response category against the corresponding category. A monotonic increasing or decreasing trend confirms the ordinality assumption.

(2) *Choosing between competing models*

To choose between competing models, the deviance statistic of competing models is compared. The difference of deviance between two models is the likelihood-ratio statistic, G^2, having null chi-squared distribution (Agresti, 2002). This is also known as Analysis of Deviance (AOD) that generalizes the Analysis of Variance (ANOVA) used in multivariate normal regression.

(3) *Checking proportional odds assumption*

To test the proportional odds assumption, a *score* test or *Wald* test can be used (Long, 1997; Hosmer, 2002).

(4) *Checking the overall fit of the selected model*

Test for overall model fit assesses whether the chosen model improves predictions over the null (intercept only) model. The likelihood ratio chi-square test can be applied for this purpose (long, 1997).

(5) *Checking the model performance*

Pearson and deviance goodness-of-fit tests can be used to compare the predicted frequency counts from the hypothesized model to the observed frequencies (Agresti, 2002).

5.4.7 Important Considerations Related To Model Estimation and Validation

Contingency tables with low and zero cell counts, as well as, with high counts in large number of cells result in *sparse* tables (Agresti, 2002) or data thinning (Hosmer, 2002). Data thinning can also occur when there are large number of variables in the model (Hosmer, 2002). Caution should be exercised in analyzing sparse data as sparseness *can* have profound effect on model estimation and goodness-of-fit tests. For example, according to Agresti (2002), in some cases the iterative estimation algorithm may fail to converge and result in a value of $+\infty$ or $-\infty$ for a model's parameters estimates. Agresti (2002) noted that: (1) *sampling* zeros are very common in contingency tables; (2) a count of 0 is a permissible outcome for a multinomial response variable (e.g., *Internal Condition Grade* in this paper); (3) low or zero counts does not always harm the analyses; (4) the sampling distributions for goodness-of-fit statistics such as likelihood ratio chi-square, X^2, and likelihood ratio deviance, G^2, can be far from chi-squared approximations in case of sparse tables, and alternative approximations, such as limiting normal for X^2 and normal for G^2 are proposed in statistical literature; and (5) X^2 and G^2 are valid for comparing nested models that differ by relatively few terms even if the data is sparse. One of the indicators of sparse data analysis problems is large estimated standard errors (Hosmer, 2002). Agresti (2002) suggested using Bayesian and random effects models to handle problematic sparse data.

5.5 Case Study

The proposed model is applied to City of Niagara Falls wastewater pipeline condition assessment data collected by the authors. The condition surveys were carried out using Side Scanner and Evaluation Technology (SSET). Demonstrated advantages of SSET over traditional CCTV pipeline inspection technologies include the ability to: complete defect rating after the survey is completed; measure pipeline defect changes over time; and more accurately code pipeline defects. Chae et al. (2003) and Knight et al. (2009) present a good discussion on the advantages of SSET over traditional CCTV inspection surveys.

5.5.1 City of Niagara Falls Pipeline Condition Assessment Data

To ensure that a high quality SSET pipeline condition assessment database is developed for the City of Niagara Falls wastewater network, the data collection and data analysis procedure, shown in Figure 5.1, was implemented. A contractor supplied North American Association of Pipelines Inspectors (NAAPI) certified operator completed all the SSET pipeline surveys, and coded all pipeline defects in accordance with the Manual of Sewer Condition Classification 3rd edition (WRc, 1993). Using NAAPI certified City of Niagara Falls personnel, a second Quality Assurance (QA) and Quality Control (QC) check was performed on all the contractor provided data.

All of the City of Niagara Falls quality pipeline inspection data was transported to the University of Waterloo to be stored on two geographically distributed data servers that are backed up using RAID 5 technology to ensure data security, availability, and seamless recovery. Using a University of Waterloo custom built software application, the City of Niagara Falls QA/QC data is uploaded into a database management system named WatBAMS (Waterloo – Buried Asset Management System). The software import utility contains further QA/QC protocols to ensure that only high quality data is uploaded in the WatBAMS database for each pipe segment survey. Using WatBAMS programmed routines, each pipeline segment is analyzed in accordance with the Sewerage Rehabilitation Manual 4th edition methodology to determine the corresponding Internal Condition Grade (ICG). WatBAMS also allows for the upload and integration with the City's of Niagara Falls GIS and inventory databases that contain each pipe segment's attributes - asset ID, location, construction date, and material type etc.

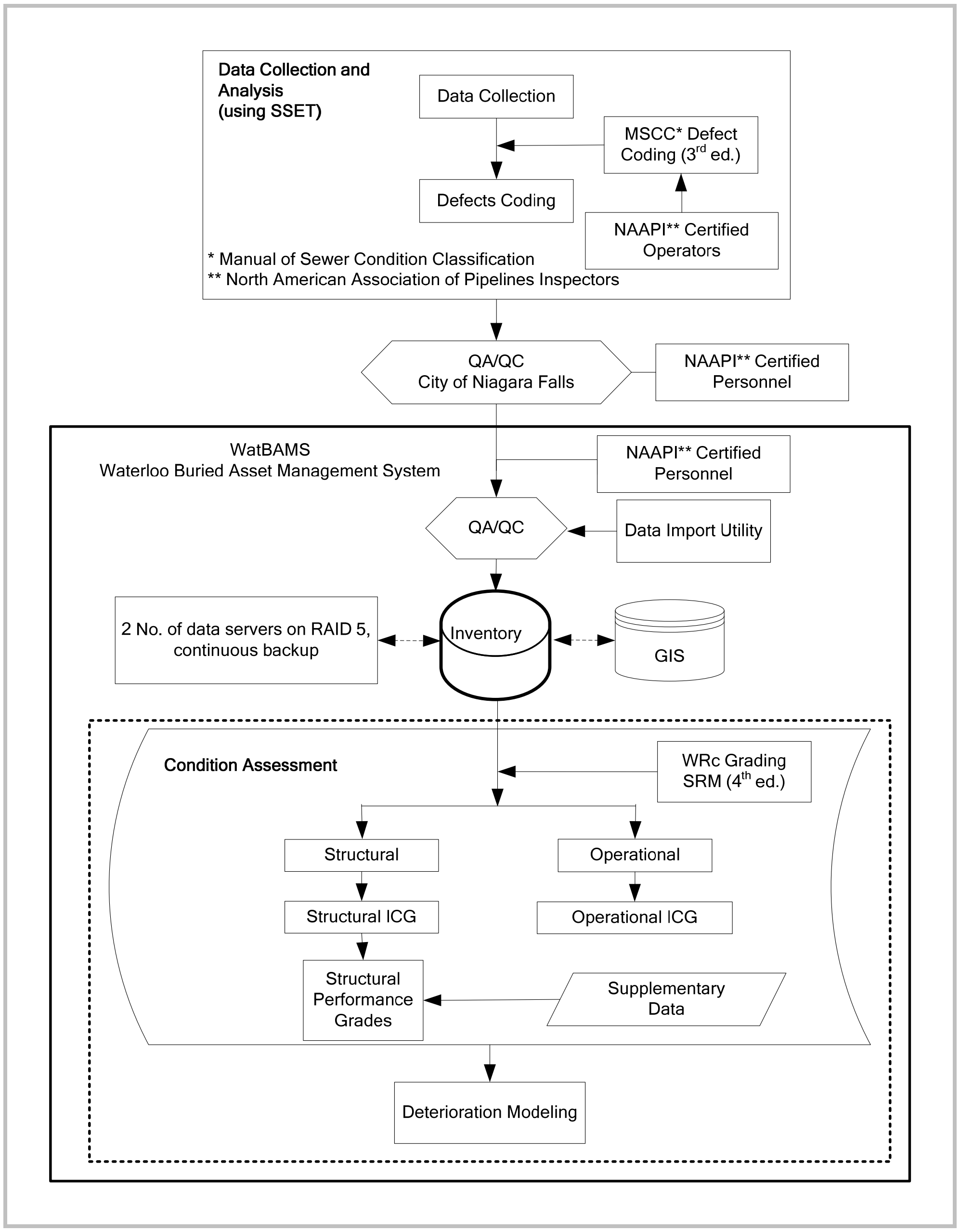

Figure 5.1: Data Collection and Analysis Framework

The City of Niagara Falls wastewater collection network consists of approximately 400 km of pipelines that has approximately 5,500 pipe segments consisting of a variety of pipe materials with ages that range from over 100 years to less than 20 years with an average age of 47 years. Figure 5.2 shows that 35% of the network consists of Reinforced Concrete (RC), 17% PVC, 10% Vitrified Clay (VC), 10% Asbestos Cement (AC), and 25% of the network has no assigned pipe material. The average age of the RC and VC pipes are 42 and 65 years, respectively. Review of the SSET surveys and defect reports found that VC pipes have open and displaced joints and service connections that were installed by creating a hole in the clay pipe. Thus, there are holes and cracks where service connections enter into the VC pipes. RC pipes were found to be generally in good condition except for locations with few displaced joints and structural defects such as cracks, fractures, and broken segments. None of the pipes in the sample were rehabilitated or replaced, and therefore, none of the observations were censored.

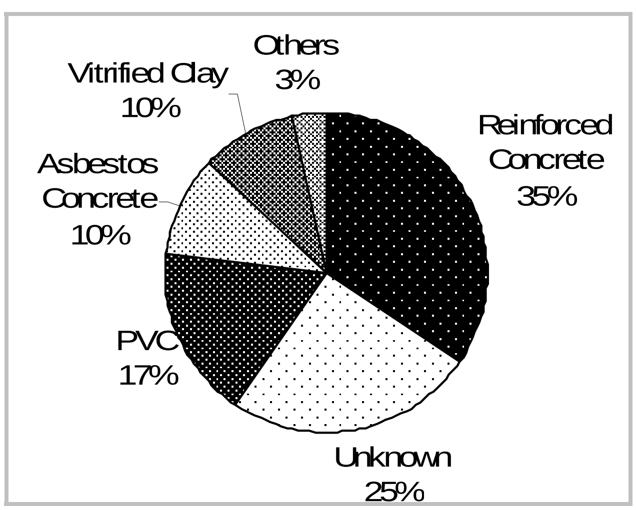

Figure 5.2: Distribution of Various Pipe Materials - City of Niagara Falls Sewer System

In the following sections, approximately 12% (45 km) of the City of Niagara Falls wastewater collection network data (collected through stratified sampling) is used to demonstrate the model development process shown in Figure 5.3. Table 5.1 presents the observed data in the form of a *contingency* table – that is, the table cells contain the frequency counts of the response variable, *Internal Condition Grade (ICG)*. Table 5.1 shows the average age of sampled pipes in each ICG as well as the pipelines frequency data classified by *material*, *age*, and *ICG*. It is noted that the average age of RC pipes in the sample – unlike the VC pipes – increases with increasing ICG (refer to Table 5.1). This provides the first indication of age related deterioration in RC pipes. Some cells in the table have low or zero counts. It is emphasized that the cells with zero counts are *sampling* zeros – that is, it is possible to have observations in these cells when more data becomes available – rather than *structural* zeros where observations are not possible. For wastewater pipelines, low counts are possible in ICG 4 and 5 for newer pipes. Similarly, there can be smaller number of observations in ICG 1, 2 and 3 for older pipes. The implications of low and zero counts on model estimation and model fit are discussed in Section 5.4.7.

The model building process involves checking the linearity of continuous predictors with the response and ordinality of response variable. If the linearity assumption is not satisfied then correct parametric form of continuous predictors need to be determined. If the response is not ordinal then alternative models such as multinomial logit may be considered. Once the linearity and ordinality assumptions are satisfied, the estimates for model parameters are determined and their statistical significance is checked. Then proportional odds assumption is checked and model validation is carried out using goodness-of-fit tests. This is followed by interpretation of results and conclusions.

Table 5.1: Pipelines Data Classified by *Material*, *Age*, and *Internal Condition Grade*

Material	**Age (years)**	**Internal Condition Grades**				
		1	**2**	**3**	**4**	**5**
Reinforced Concrete	0-20	7				
	20-40	131	13	13	18	3
	40-60	24	8	7	8	5
	60-80	1		1	1	
	80-100		1	1	2	3
	100-120					2
	Avg. Age (std. dev.)	35.7(10.7)	44.7(15.2)	43.7(14.9)	47.1(18.1)	61.9(27.7)
Vitrified Clay	0-20	1				1
	20-40	4	1	1	3	5
	40-60	8		6	8	7
	60-80	3		1	1	1
	80-100	4			9	5
	100-120	6		1	3	10
	Avg. Age (std. dev.)	66.5(27.2)	31.7	59.6(24.9)	67.5(23.2)	65.1(31.6)

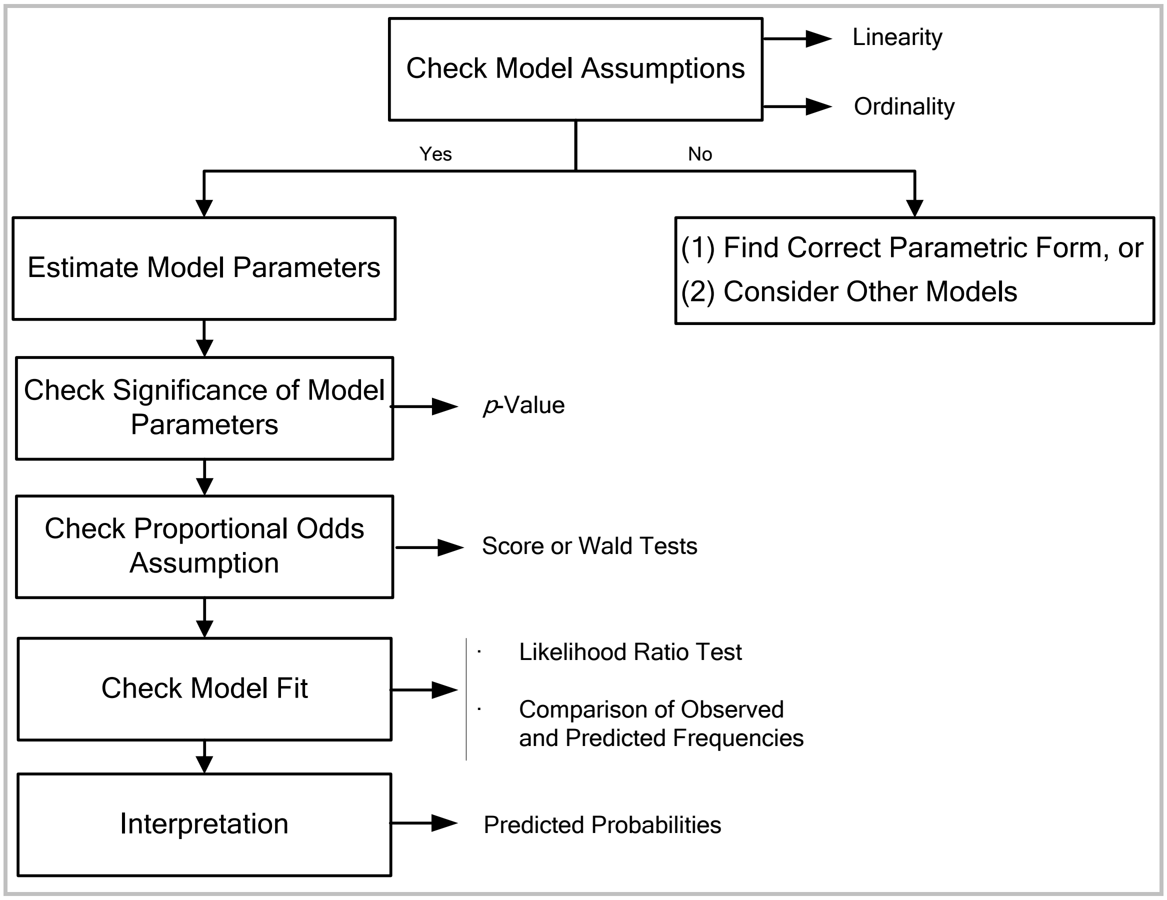

Figure 5.3: Modeling Flow Chart

5.5.2 Linearity and Ordinality Assumptions Verification

The verification of the linearity in logit for the *age* variable is carried out using quartiles (Bender 1998, Hosmer 2002) and fractional polynomial analyses (Royston and Altman, 1994). As there are five condition grades (categories), there will be four cumulative logits, namely, Case I: Category 1 vs. Categories 2, 3, 4, and 5 combined; Case II: Categories 1 and 2 combined vs. Categories 3, 4, and 5 combined; Case III: Categories 1, 2, and 3 combined vs. Categories 4 and 5 combined; and Case IV: Categories 1, 2, 3, and 4 combined vs.

Category 5. The quartiles analyses for three of the four cumulative logits i.e., Cases I, II, and IV, reveal the linearity in logit for *age* variable, however the relation appears to be non-linear for Case III. The non-linear and one of the linear cases are illustrated in Table 5.2 and Figure 5.4. Figure 5.4(a), which plots Case II shows a linear relation between logit coefficients and age quartiles; however the relation shown in Figure 5.4(b) (Case III) is not linear. Therefore, the correct parametric form for the age variable need to be determined.

Table 5.2: Quartiles Analyses for Checking Linearity Assumption

		Quartile	1	2	3	4
		Cutoff	25th percentile	50th percentile	75th percentile	Highest 25%
		Age Interval (Years)	3.8 - 27.8	27.9 - 33.8	33.9 - 50.3	50.4 - 105.9
		Age Midpoint (Years)	16.3	31.4	42.6	78.7
Case II Figure 5.4(a)	Grades 1 and 2 combined vs. all above	Logit coefficients	0.000	-0.709	-1.043	-2.229
Case III Figure 5.4(b)	Grades 1, 2, and 3 combined vs. all above	Logit coefficients	0.000	-0.036	-0.358	-1.724

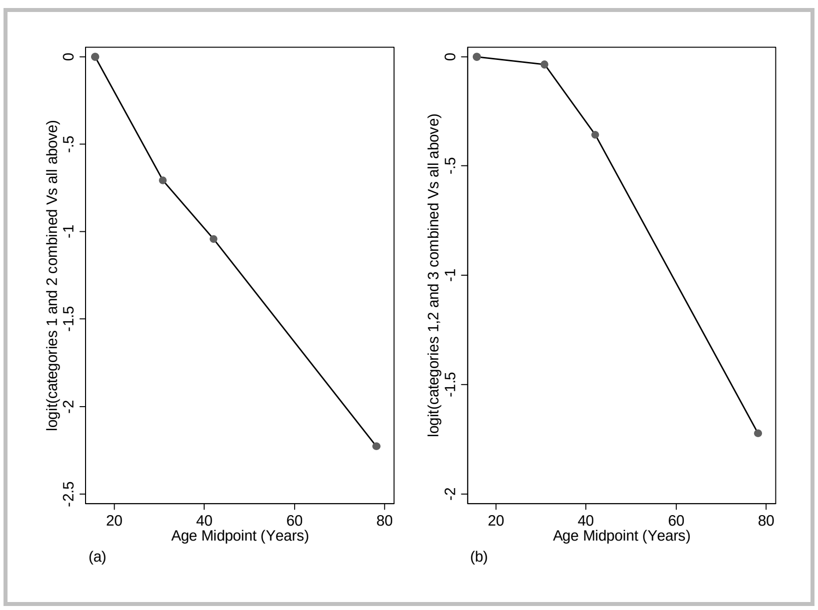

Figure 5.4: Linearity of Response with *age* (Younis and Knight, 2008)

To find out the correct parametric form for the *age* predictor, a Fractional Polynomial Analysis (FPA) is performed. The FPA results are shown in Table 5.3, and reveal that the deviance statistic is minimum (i.e., 245.5) for model M1. That is, the model M1 is the best fitting non-linear transformation which contains *age* and age^3 terms. Model M1 is compared with the linear model (also shown in Table 5.3). The likelihood ratio test statistic, G^2 (i.e., deviance for linear model minus the deviance for model M1) = 1.197. The significance level, *p*-value is $\Pr\left(\chi^2\left(3\right) \geq 1.197\right) = 0.754$ for three degree of freedom. Since the *p*-value is greater than 0.05, model M1 is not significantly different from the linear model. Similar analyses for the three cumulative logits found that the assumption of linearity in logit for *age* is reasonable.

Table 5.3: Fractional Polynomial Analysis

Model	**df**	**Deviance**	G^2	**p-value**	**Powers**
Not in model	0	278.212	32.703	0	
Linear	1	246.706	1.197	0.754	*age*
M1: Non-linear	4	245.509			*age*, age^3

To verify the ordinality of response variable i.e., Internal Condition Grades (ICG) with respect to the continuous predictor, *age*, a simple graphical technique proposed by Harrell (2001) is used. It involves the plot of mean values of age within each ICG category against the corresponding condition grades. Figure 5.5 shows how different ICG categories are related to the mean of *age*. From the monotonic increasing trend it evident that the response variable, ICG, acts in an ordinal manner with *age*. In Figure 5.5, the mean values of *age* for Grades 1 and 2 were indistinguishable, so the two grades were pooled. Figure 5.5 also shows the plot (dotted line) for expected value of *X,* i.e., *age*, conditional on being in a certain condition grade, $Y = j$ provided that the proportional odds assumption is true. Since the dotted curve in Figure 5.5 shows approximately the same trend as the solid line, therefore, the proportional odds assumption for age is deemed to be reasonably satisfied.

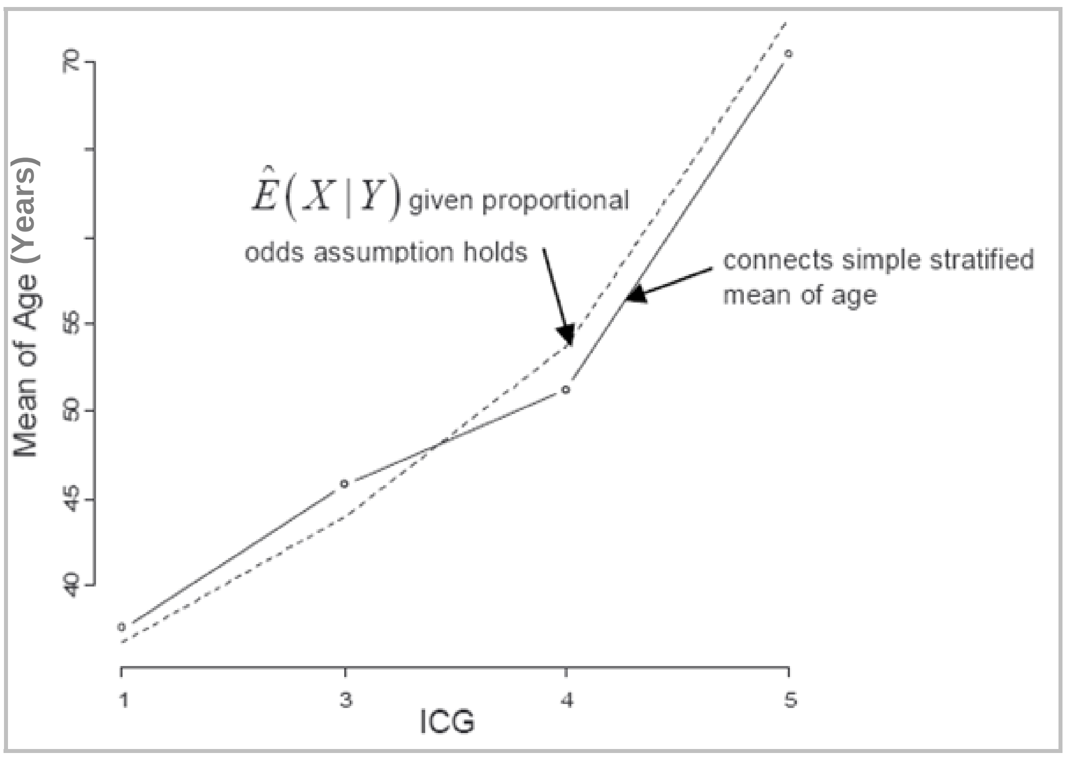

Figure 5.5: Ordinality of Response with *age*

5.5.3 Parameter Estimates

Once the linearity and ordinality assumptions are verified a series of ordinal models are fitted to systematically include, and analyze the *material* and *age* variables, and their interaction $age \times material$. The results are presented in Table 5.4, where Model 1 contains the pipe *material* predictor only; Model 2 contains pipe *age* and *material*; and Model 3 contains the predictors, pipe *age* and *material* along with the term $age \times material$ representing the interaction between the two predictors. The estimates for $(J-1)$ cutpoints, μ_j, are shown for Model 3 only. The change in deviance (or likelihood ratio test) statistic, G^2, along with corresponding *p*-value is also provided in Table 5.4 to compare the models.

The estimate for *material* predictor changed from -1.853 in Model 1 to -1.064 in Model 2, a change of 74.2%. This large change in parameter estimate for pipe *material* when *age* is added to the model suggests a strong association of *age* with the probabilities of being in various internal condition grades. The mean *age* for VC and RC pipes in the sample is 67 and 37 years, respectively. This difference in mean *age* for the two pipe materials also contributed to the change in parameter values for the *material* predictor in Models 1 and 2. When Model 2 is compared with Model 1, the likelihood ratio test statistic, G^2, is 25.31 with *p*-value < 0.0001. Since *p*-value is less than 0.05, the change in deviance is significant, and therefore, Model 2 is better than Model 1.

To determine the effect of *age* on the response variable (i.e., probabilities of being in certain condition grades) for the two pipe materials, Model 3 contains the interaction term

$age \times material$ in addition to *age* and *material* predictors. In Model 3, it is interesting to note that the coefficient of *age*, $\hat{\beta}_2$, becomes non-significant as $p = 0.223$ is greater than the generally accepted statistical significance level of 0.05. Using Equation 5.2, Model 3 can be estimated as:

$$\text{logit}\left[\hat{P}\left(Y \leq j \mid \text{material,age,}\hat{\mu}\text{,}\hat{\beta}\right)\right] = \hat{\mu}_j - \hat{\beta}_1\text{material} - \hat{\beta}_2\text{age} - \hat{\beta}_3\text{material} \times \text{age} \quad (5.7)$$

A dummy/indicator variable that equals 0 in case of Vitrified Clay (VC) and 1 for Reinforced Concrete (RC) is used for the *material* predictor. Therefore, for VC pipes, the right hand side of Equation 5.7 reduces to: $\hat{\mu}_j - \hat{\beta}_2\text{age}$. The coefficient for age, $\hat{\beta}_2 = 0.008$ for VC pipes, which is not significant as discussed above. Thus, *age* is not related to the response for VC pipes. For RC pipes, the right hand side of Equation 5.7 becomes: $\hat{\mu}_j - \hat{\beta}_1 - \left(\hat{\beta}_2 + \hat{\beta}_3\right)\text{age}$. The parameter estimate for *age* for RC pipes is: $\hat{\beta}_2 + \hat{\beta}_3 = .008 + .046 = .055.$ The significance of $(\hat{\beta}_2 + \hat{\beta}_3)$ is tested using method of contrasts (Hosmer, 1999) which results in Wald statistic, $z = 6.50$ with p-value < 0.0001, which is significant. Therefore, *age* is related to the response for RC pipes. When Model 3 is compared with Model 2, the likelihood ratio test statistic, $G^2 = 18.26$ with p-value < 0.0001. Since the p-value is less than 0.05, Model 3 is determined to be statistically better than Model 2.

The model applied to the City of Niagara Falls data is a proportional odds model, i.e., it is a fully constrained model and assumes the same effects, β, for each logit. The assumption of proportional odds is tested using approximate likelihood ratio test (Agresti, 2002; Long, 1997) where the null hypothesis states that the constrained model fits, as well as, the unconstrained model. The likelihood ratio test statistic, G^2 = 3.85 with *p*-value = 0.2785, which is not unlikely under the null hypothesis. Therefore, we fail to reject the null hypothesis, and the assumption of proportional odds is plausible. Thus, there is only one estimated coefficient for each predictor and their interaction across all the cumulative logits.

Table 5.4: Estimated Coefficients; the Likelihood Ratio (LR) Test Statistics, G^2; and *p*-value for the Change for Models

Model	**Variable**	**Coeff.**	**Std. Err.**	**z**	**P>z**	**[95% Conf.**	**Interval]**	G^2	***p*-value**
1	*material*, β_1	-1.853	0.247	-7.490	0.000	-2.338	-1.369		
2	*material*, β_1	-1.064	0.292	-3.640	0.000	-1.636	-0.491	25.31	< 0.0001
	age, β_2	0.028	0.006	4.980	0.000	0.017	0.038		
3	*material*, β_1	-3.439	0.633	-5.430	0.000	-4.680	-2.198	18.26	< 0.0001
	age, β_2	0.008	0.007	1.220	0.223	-0.005	0.022		
	age × *material*, β_3	0.046	0.011	4.190	0.000	0.025	0.068		
	cut1, μ_1	-0.714	0.514			-1.721	0.294		
	cut2, μ_2	-0.352	0.512			-1.356	0.652		
	cut3, μ_3	0.199	0.512			-0.804	1.203		
	cut4, μ_4	1.491	0.528			0.456	2.527		

5.5.4 Model Validation

The validation, that is, the degree to which predicted outcomes match with the observed outcomes, or how well the model describes the data (Hosmer, 2001) is carried out as explained below:

The first test, *likelihood-ratio chi-square (LR chi-square)* compares the hypothesized model to the null or intercept only model (Long, 1997; O'Connel 2006). LR chi-square statistic provides an overall test of the null hypothesis that all the β coefficients for all the variables in the model are 0. For the proposed model, the LR $\chi_3^2 = 110.390$ (p-value < 0.0001) . This is significant as p-value is less than 0.05. Therefore, the model with the predictors performs better than the intercept only model.

Secondly, the expected frequencies from the hypothesized model are compared with the observed frequencies to check the model performance. For this purpose, two measures, Pearson and Deviance goodness-of-fit, are computed, and results are shown in Table 5.5. The observed significance of both the measures is large (i.e., > 0.05), and therefore, it appears that the proposed model fits the data well.

Table 5.5: Goodness-of-fit Statistics

	Chi-Square	df	Sig.
Pearson	35.792	41	.701
Deviance	43.752	41	.355

Furthermore, Table 5.6 presents the predicted/expected and observed outcome frequencies for RC and VC pipes with age along with the standardized Pearson residuals. None of the residuals are greater than 2 in absolute value which substantiates that the model fits well to the observed data. The model predicted frequencies also conform closely to the observed frequencies, and hence the model demonstrates a good representation of the City of Niagara Falls wastewater collection system condition assessment data.

The smaller standard errors in our analysis (refer to Table 5.4) indicate that there are no problems with the parameter estimates (i.e., estimation algorithm did converge and parameter estimates are stable). X^2 and G^2 statistics are used to compare nested models – that is, comparing the selected model (model 3) with the null model, and to choose the best fitting model amongst competing models (model 1, 2, and 3). Table 5.6 shows that predicted counts match with the observed counts, and none of the Pearson Residuals are greater than ± 2. Therefore, model performs well in predicting the ICG of wastewater pipelines in the City of Niagara Falls.

Table 5.6: Model Performance – Observed and Predicted Counts

Material	Age		Internal Condition Grade (ICG)				
			1	2	3	4	5
RC	0-20	Observed	7	0	0	0	0
		Expected	6.071	.255	.269	.289	.117
		Pearson Residual	1.035	-.514	-.529	-.549	-.344
	20-40	Observed	131	13	13	18	3
		Expected	133.231	11.000	12.584	14.796	6.389
		Pearson Residual	-.385	.622	.122	.870	-1.365
	40-60	Observed	24	8	7	8	5
		Expected	26.017	4.646	6.440	9.717	5.180
		Pearson Residual	-.559	1.631	.236	-.611	-.084
	60-80	Observed	1	0	1	1	0
		Expected	.722	.216	.385	.900	.777
		Pearson Residual	.375	-.482	1.063	.125	-1.024
	80-100	Observed	0	1	1	2	3
		Expected	.713	.267	.560	2.000	3.460
		Pearson Residual	-.891	1.447	.613	.000	-.348
	>100	Observed	0	0	0	0	2
		Expected	.073	.030	.069	.339	1.488
		Pearson Residual	-.276	-.175	-.268	-.639	.830
VC	0-20	Observed	1	0	0	0	1
		Expected	.585	.160	.269	.563	.423
		Pearson Residual	.646	-.417	-.558	-.886	.999
	20-40	Observed	4	1	1	3	5
		Expected	3.753	1.071	1.850	4.075	3.251
		Pearson Residual	.149	-.071	-.671	-.632	1.107
	40-60	Observed	8	0	6	8	7
		Expected	6.980	2.088	3.717	8.704	7.510
		Pearson Residual	.443	-1.500	1.268	-.285	-.216
	60-80	Observed	3	0	1	1	1
		Expected	1.205	.385	.717	1.856	1.836
		Pearson Residual	1.830	-.642	.356	-.756	-.741
	80-100	Observed	4	0	0	9	5
		Expected	3.522	1.136	2.127	5.582	5.633
		Pearson Residual	.284	-1.101	-1.553	1.742	-.322
	>100	Observed	6	0	1	3	10
		Expected	3.342	1.129	2.187	6.227	7.115
		Pearson Residual	1.593	-1.094	-.850	-1.558	1.347

5.5.5 Model Interpretation

The problem is formulated as to determine the probability of wastewater pipelines being in a specific category of Internal Condition Grades (ICGs) given covariates and their possible interactions. To accomplish this objective, the interpretation is carried out in terms of probabilities of outcomes given as:

$$\hat{P}(Y = j \mid \mathrm{x}) = F\left(\hat{\mu}_j - \hat{\beta}_j \mathrm{x}\right) - F\left(\hat{\mu}_{j-1} - \hat{\beta}_j \mathrm{x}\right) \tag{5.8}$$

Specifically, the interest is to compare the predicted probabilities of being in ICGs of 1 to 5 for Vitrified Clay (VC) and Reinforced Concrete (RC) wastewater pipelines and to determine if it changes with *age*. The significant interaction term, $material \times age$ suggests that the effect of *age* varies by the type of pipe *material*.

For RC pipes, *age* is related to the degradation. Figure 5.6 shows the predicted probabilities of being into one of the five ICGs with *age*. The probabilities of the lowest and highest response categories (i.e., ICG = 1 and ICG = 5) are monotonic functions of *age*, whereas, the probabilities of the intermediate categories (i.e., ICG = 2, 3, and 4) are unimodal or single-peaked functions. Thus, the effect of *age* on the probability of being in grade 1 is negative i.e., the probability of a pipeline being in acceptable condition decreases with the *age* of pipe. On the other hand, the effect of *age* on the probability of being in grade 5 is positive, i.e., the probability of a pipeline being in grade 5 increases with *age*. The predicted probabilities of being in intermediate grades first increase with *age*, and then decrease after certain *age* thresholds. For example, for RC pipes, the probability of being in ICG = 3 first increases until the age of about 55 years, and then decreases. This occurs because as the age increases, more cases move into condition 3 than leave from 3 to other worse categories. Therefore, the probability of being in condition 3 increases. As the age is increased beyond 55 years, cases entering condition 3 are less than the cases leaving, thus the probability decreases. Based on our analysis, the probabilities of being in grade 5 (collapsed or collapse imminent) for RC pipes exceed the probabilities of being in lower grades at about 75 years for the sample data collected from the City of Niagara Falls wastewater collection system.

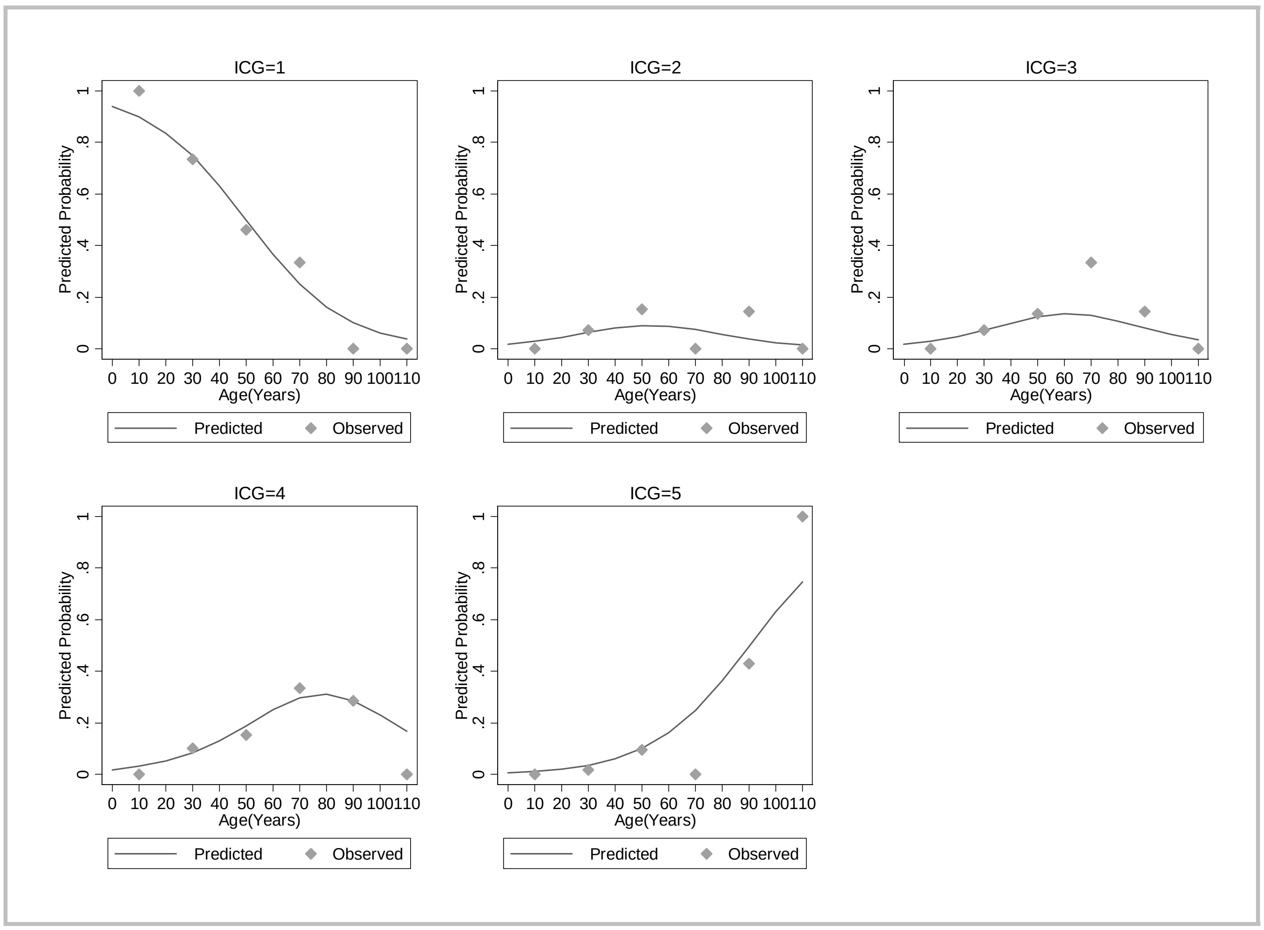

Figure 5.6: Predicted Probabilities for RC Pipes

For VC pipes, *age* is not related to the probabilities of being in certain ICGs. This is shown in Figure 5.7 which also compares the predicted probabilities of RC and VC pipes – note there is little change in predicted probabilities for VC pipes with *age* for each ICG. It is also determined that VC pipes have marginally higher probabilities of being in higher grades as compared to RC pipes, however, the probability of being in grade 5 for RC pipes surpasses the probability for VC pipes after about 75 years of age.

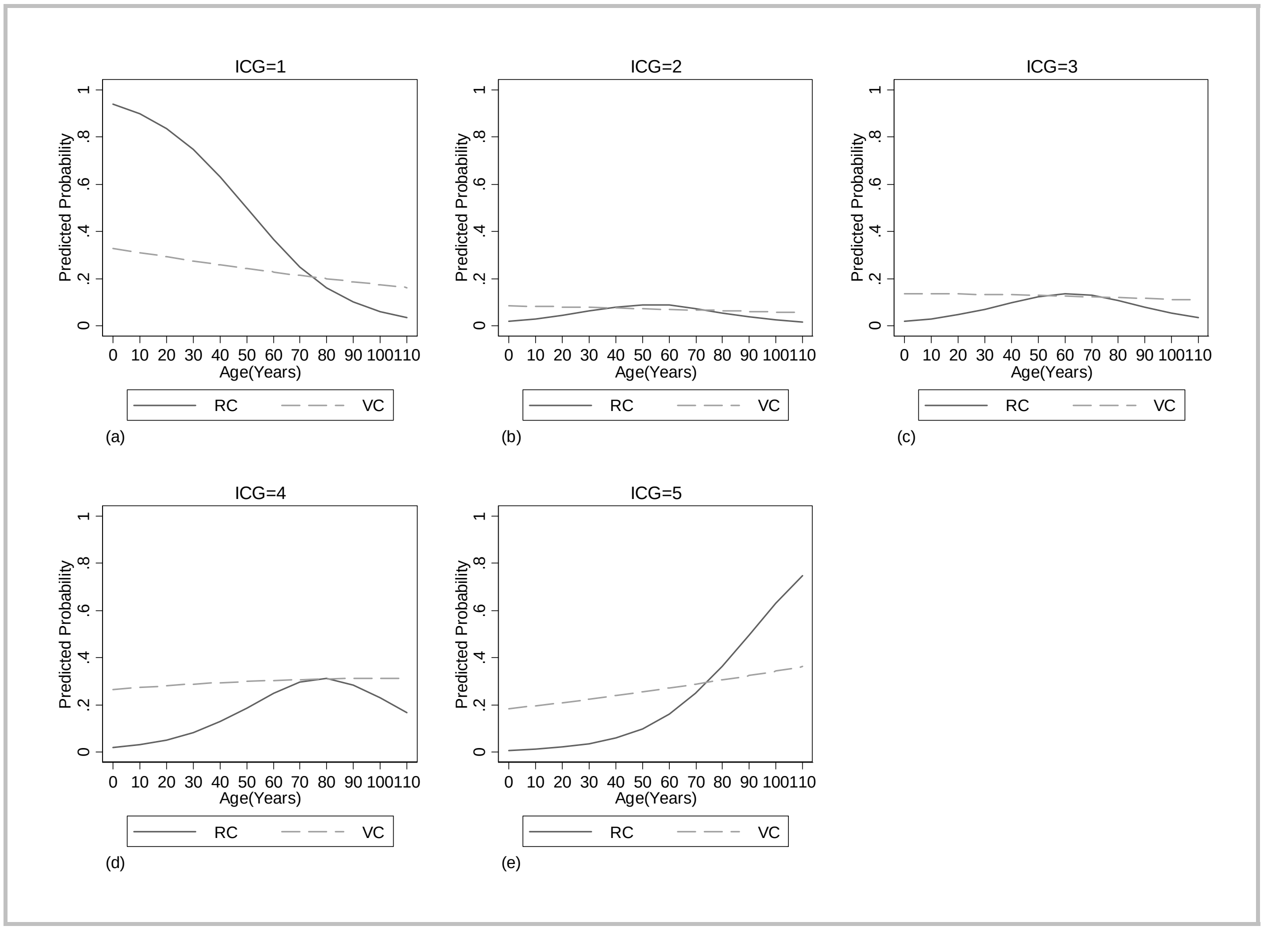

Figure 5.7: Comparison of Predicted Probabilities for RC and VC Pipes

The probabilities of being in worse condition grades are marginally higher for VC pipes as compared to RC pipes. This finding is not attributable to the older age of VC pipes. The relatively higher probabilities of being in worse condition grades for VC pipes as compared to RC pipes may be due to: (1) poor installation practices; (2) excessive loading during their lifespan; and/or (3) soil loss due to infiltration/ex-filtration through open joints and defective connections. The majority of the inspected VC pipes in the system were found to have open and displaced joints which might be due to poor installation practices. Laterals connections were also found to be defective which could result in cracks, fractures, and holes in the VC pipes.

5.6 Conclusions

Better deterioration models are needed to understand the performance of wastewater pipelines and to make future predictions about their condition. A new cumulative logit deterioration model for wastewater pipelines is developed and applied to the City of Niagara Falls wastewater collection system. The model provides valuable information in terms of predicted probabilities of being into one of the five Internal Condition Grades (ICGs) for wastewater pipelines. It is emphasized that the conclusions presented in this paper are based on our analysis of a sample of condition assessment data from the City of Niagara Falls wastewater collection system. The data was captured using Side Scanner Evaluation Technology (SSET) and defect coded using the 3rd edition of WRc's Manual of Sewer Condition Classification by NAAPI certified operators and analysts. The pipelines' condition is assessed using defect scores from the 4th edition of WRc's Sewerage Rehabilitation

Manual using a custom built non-proprietary software application, WatBAMS, developed by the authors.

The deterioration in RC pipes was found to be age related. Since RC pipes are prone to corrosion due to hydrogen sulfide and moisture in addition to other reactive agents in domestic sewage, material loss and deterioration will occur over time. Thus, the finding that the probability of being in certain ICG is age related for RC pipes is deemed reasonable. Based on our analysis, the service life for RC pipes is approximately 75 years for the City of Niagara Falls wastewater pipelines data. VC pipes were found to last indefinitely provided they are installed in good condition and are not subject to installation damage or excessive loadings. This indefinite service life is greater than the current assumed life of 80 years.

The cumulative logit model was found to accurately predict both RC and VC pipelines deterioration. This model can be used to determine the wastewater pipelines service life, predict future condition states, and future rehabilitation and maintenance needs. The model can also be used to develop realistic future maintenance and operation budgets over the life of the asset and to satisfy regulatory reporting requirements. Further research is required to validate the cumulative logit model in other networks and to model the deterioration of pipe materials other than RC and VC.

Acknowledgments

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Chapter 6

Continuation-ratio Model for the Performance Behavior of Wastewater Collection Networks

This paper has been submitted to the Tunneling and Underground Space Technology journal.

6.1 Abstract

Canada's aged wastewater infrastructure is rapidly failing. New financial and environmental regulatory requirements demand the municipalities to estimate operating and capital expenditures for running the systems into the future, and come up with plans for financial sustainability keeping in view the public health and environmental protection. Wastewater pipelines' deterioration is not well understood, and realistic deterioration models need to be developed for effective and efficient maintenance management of wastewater collection systems.

This paper presents a new ordinal regression model for the deterioration of wastewater pipelines based on *continuation ratio* logits. The model is presented using the *generalized linear* model formulation, and takes into account the ordinal nature of dependent variable and interaction effects between explanatory variables. The model provides estimates of conditional probabilities for a pipeline to advance beyond a particular internal condition grade – to worse condition – depending on pipe *material* and *age*. The model development and validation procedure is demonstrated using high quality condition assessment data for Reinforced Concrete (RC) and Vitrified Clay (VC) pipes from the City of Niagara Falls wastewater collection system.

The new model was found to represent the RC and VC pipes degradation behavior for in service pipes up to 110 years of age for the City of Niagara Falls wastewater collection system. RC pipes deterioration was found to be age dependent while VC pipes deterioration was not age dependent. This finding is contrary to other deterioration model studies that

indicate that type of pipe material is not significant and that the deterioration of VC pipes is also age dependent. The present analysis shows, for example, that the predicted conditional probability for RC pipes to advance beyond internal condition grade 3 is estimated to be 60% at 40 years of age, and it increases to 90% at 80 years. Similarly, there is a 60% chance of advancing beyond grade 4 to collapsed/collapse imminent condition at 80 years of age for RC pipes. VC pipes were found to have an indefinite service life if installed without structural damage. However, VC pipes exhibited relatively higher conditional probabilities of advancing to worse internal condition grades as compared to RC pipes up to 60 years of age. This is attributable to poor installation practices that resulted into pipe defects such as open/displaced joints and defective connections.

The findings from the presented continuation ratio model can be used for risk-based policy development for maintenance management of wastewater collection systems. The proposed model can help in devising appropriate intervention plans and optimum network maintenance management strategies based on pipelines' age, material type, and internal condition grades. This is critical to develop realistic wastewater networks' future maintenance and operation budgets for the life of asset, and to meet new regulatory reporting requirements. Further research is required to validate this model for other networks, and modeling deterioration of pipe materials other than RC and VC.

Keywords: Wastewater pipelines; Deterioration modeling; Continuation ratio model; Ordinal regression; Asset management; Sewer systems.

6.2 Introduction

A large percentage of Canada's buried municipal water and wastewater piping networks have exceeded or are approaching its design life of 50 to 75 years. Therefore, this aging and deteriorating infrastructure needs to be renewed or replaced. Estimates of Canada's municipal infrastructure deficit vary from a $44 billion total municipal infrastructure shortfall (TD Economics, 2002) to over $125 billion (Mirza, 2007). The *municipal infrastructure deficit* is an estimate of the total additional investment needed to repair and prevent deterioration in existing, municipally owned infrastructure assets. Mirza (2007) reports that the infrastructure funding gap for existing water and wastewater is $31 billion, and to meet new needs an additional $56.6 billion is required. The size and scope of the infrastructure problems facing municipalities and local governments is enormous as the decay of Canada's infrastructure creates severe domino effects – higher cost of maintenance, operation, rehabilitation, and repair; inefficiency and increased vulnerability; and increased threats to public safety and the environment. Mirza (2007) states that "without maintenance or with deferred maintenance, the municipal infrastructure deficit could be close to $2 trillion by 2065, and that with regular maintenance and good scientific management, the escalating infrastructure deterioration and the resulting infrastructure deficit can be controlled within manageable levels."

In 2006, the Canadian Institute of Chartered Accountants Public Sector Accounting Board (PSAB) issued statement PS3150 which requires all Canadian municipalities and utilities, starting in January 2009, to report their tangible capital assets along with their depreciation on financial statements (OMBI, 2007). One of the PSAB requirements is the estimation of operating and capital expenditures for running the systems into the future. In the United States, the Governmental Accounting Standards Board (GASB) Statement 34, and in Australia, the Australian Accounting Research Foundation Standard 27 specify similar accounting practices (see FHWA, 2000; Howard, 2001). To meet these specified accounting practices, knowledge on how the assets behave and deteriorate over time is imperative.

Current Canadian government guidelines suggest the useful life for various civil infrastructure assets. For example, for wastewater pipelines, the estimates of useful service life may range from 40 to 75 years with limited or no asset deterioration knowledge according to Ministry of the Environment, Ontario (2007) and NAMS (2002). The absence of asset deterioration knowledge necessitates Canadian municipalities to make unsubstantiated assumptions about the timing and volume of capital expenditures so that they can comply with PSAB and other government and regulatory requirements. These unsubstantiated assumptions will most likely result in an under or over-estimation of assets future operational and capital needs. To develop realistic future life-cycle asset operation and maintenance financial needs it is imperative that asset deterioration behavior is understood and realistic deterioration models are developed and used for future predictions.

This paper provides an overview of wastewater condition assessment methodology and protocols. It also discusses ordinal regression models and their applications in civil engineering. An ordinal regression model, based on *continuation ratios* is developed and described along with its assumptions and estimation procedure for predicting wastewater infrastructure deterioration. The new deterioration model is demonstrated using the City of Niagara Falls wastewater collection system pipeline condition assessment data. The procedures for verification of assumptions, determination of parameter estimates, validation, and model interpretation are presented. The paper concludes with a discussion on the results, and deterioration model limitations.

6.3 Literature Review

A review of current industry practices with respect to wastewater pipelines condition assessment and deterioration modeling is provided in the following sections.

6.3.1 Condition Assessment of Wastewater Pipelines

Remotely controlled Closed Circuit Television (CCTV) and more recently Side Scanning Evaluation Technology (SSET) cameras also known as Sewer Scanner and Evaluation Technology (SSET^{TM}) are used for visual inspections of interior of wastewater pipelines. Pipeline inspections are completed by an operator remotely moving the camera down the pipeline and coding all observed defects using a defect condition coding system. In North America, two wastewater pipeline defect condition Classification systems are predominately used: (1) Manual of Sewer Condition Classification (MSCC) 3rd edition defect coding system developed by Water Research Center (WRc) in the United Kingdom; and (2) Pipeline Assessment and Certification Program (PACP) developed by National Association of Sewer Service Companies (NASSCO) and WRc.

The Manual of Sewer Condition Classification, first published in 1980, became the national standard in UK and many other parts of the world. In 1994 and 2004, the 3rd and 4th editions of MSCC were published by WRc, respectively. In 1994, the North American Association of Pipeline Inspectors (NAAPI) adopted WRc's MSCC 3rd edition and developed a Certification program for CCTV operators and reviewers. In 2002, NASSCO published PACP to meet the needs of the United States. The Sewerage Rehabilitation Manual (SRM), also published by WRc, describes a wastewater pipelines renovation decision making process that is adopted in the United Kingdom and Canada. The first edition of the SRM was published in 1986 and the current fourth edition was published in 2001. The SRM determines the structural and operational performance of wastewater pipelines by assigning scores to MSCC defects based on their type and severity. The structural defect scores are transformed – based on pipeline's peak defect score – to structural Internal Condition Grade (ICG) of 1 to 5, with 1 being the best or acceptable and 5 being the worst or near collapsed state. The continued use of the SRM methodology, in United Kingdom and Canada since 1994, validates the methodology as an acceptable and good approach for determining pipeline current condition states. The general principles of the SRM also form the basis for the European Standard EN752-5 – Drain and Sewer Systems Outside Buildings: Part 5 Rehabilitation. This further validates the SRM approach. NASSCO's PACP manual contains a pipeline condition rating scheme that varies from 1 to 5. The PACP condition rating depends on average score (total defects score divided by the number of defects) rather than peak score as used by the WRc. Unlike WRc's SRM, the PACP manual has no detailed decision making process. Presently, limited published data exists to validate the PACP defect scores rating system in North America. According to Stantec (2009), usage of average scores instead of peak scores for condition rating is a limiting issue of PACP methodology. PACP methodology, therefore, may not be able to accurately prioritize rehabilitation needs of wastewater collection systems (Stantec, 2009).

In 2004, the Ministry of Finance in Ontario, Canada, completed a survey to investigate municipal water and wastewater systems asset management practices. This survey found that among the responding Ontario municipalities, 17% do not perform inspections for condition assessment, and of those who do perform inspections, 33% do not record the results of the inspections (PricewaterhouseCoopers, 2003). The survey also found that large municipalities (more than 50,000 populations) typically have better asset management practices and that asset management approaches range from “don’t fix it if it is not broken” strategies to the use of computationally intensive and sophisticated software tools. This survey demonstrates the current state-of-art in asset management by municipalities in Canada and most likely in North America.

6.3.2 Wastewater Pipelines Deterioration Models

State-of-the-art techniques for deterioration modeling of wastewater pipelines include: (1) expert judgment, (2) expected value methodology, (3) binary logistic regression, (4) ordinal probit regression, and (4) Markov chains. Kathula et al. (1999) proposed a Sanitary Sewer Management System (SSMS) based on experts’ opinion. Wirahadikusumah et al. (1999) developed a Markov chains model for deterioration of wastewater pipelines. The transition probabilities matrix for Markov chains model was developed on the basis of discussions with asset managers. Baik et al. (2004); Wirahadikusumah et al. (1999); Wirahadikusumah et al. (2001); and Wirahadikusumah (2003) used the expected value approach to compute transition probabilities for deterioration models based on Markov chains. Their approach involved categorization of pipelines based on material, soil type etc. Then, regression curves were developed for each category by regressing between pipelines condition and *age*. Davies et al. (2001) and Ariaratnam et al. (2001) used binary logistic regression for modeling wastewater pipelines' deterioration. The response variable i.e., wastewater pipelines' internal condition grades were modeled as a binary/dichotomous variable that could take values either 1 or 0, corresponding to good/non-deficient or failed/deficient states, respectively. Baik (2003); Baik et al. (2006); and Jeong et al. (2005) used ordered probit regression using latent variable formulation to develop deterioration curves for wastewater pipelines. The estimated probabilities from the ordered probit model were described as transition probabilities of Markov chains to model the deterioration of wastewater pipelines as a stochastic process. Micevski et al. (2002) employed Bayesian multinomial analysis to compute transition probabilities of Markov chains model for storm water pipelines.

Summary of Key Findings

Expert probability estimates, while commonly used in decision analysis when data is not available or knowledge is vague, can be highly inaccurate. Meyer and Booker (1991) discussed issues such as bias and calibration of expert judgment, and acknowledged that humans are not good estimators of probability values and predictions. Asking experts to assign probability values to predict the likelihood of the occurrence some event, or to comment on the condition of an asset without inspection is too much to ask.

Ariaratnam et al. (2001); Baik et al. (2006); and Davies et al. (2001) concluded that the type of pipe material was not a significant factor in deterioration. Davies et al. (2001) further concluded that concrete and vitrified clay pipes exhibited identical risk of failure, and *age* was not a significant variable. Ariaratnam et al. (2001), however, found that *age* had significant effect on deterioration. The model proposed by Baik et al. (2006) was overly complex in terms of number of parameters to be estimated/interpreted, and therefore, some of their conclusions were uncertain. The expected value methodology employed by Baik et al. (2004); Wirahadikusumah et al. (1999); Wirahadikusumah et al. (2001); and Wirahadikusumah (2003) tend to violate model assumptions as it did not take into account the discrete and rank-ordered nature of condition assessment data. Micevski et al. (2002) concluded that pipe *material* and *age* affect deterioration. All the above cited studies ignored the interaction effect between pipe *age* and *material*.

Majority of the data used in the above cited studies were obtained from third party sources with limited information on data collection, and coding consistency and uniformity. Furthermore, some datasets were reported to have quality assurance and quality control problems, and missing information such as asset *age*. The development of deterioration models using poor quality datasets is challenging due to difficulties in rationalizing the findings, and possible inconsistencies between model predictions and observed field behavior.

Deterioration of wastewater pipelines is assessed in discrete and ordinal (i.e., non-continuous) measures – in terms of structural Internal Condition Grades (ICGs) or Structural Performance Grades (SPGs). The statistical techniques that take into account the ordinal information are discussed in the following section.

6.3.3 Ordinal Regression Models for Wastewater Pipelines Deterioration

Ordinal variables are a type of categorical variables that have natural ordering of categories, however, the distances between the categories is not known (Agresti, 2002). Ordinal regression models are extensively used in social and life sciences, epidemiology, and biomedical research for analyzing data where response variable is rank-ordered or ordinal. These models are extensions of binary *logit* and *probit* models to polytomous response cases. The difference between logit and probit models is in the distribution of error terms. In case of probit models, the errors are normally distributed, whereas in case of logit models, the errors are logistically distributed. The choice between logit and probit link functions is arbitrary and depends on how well the models fit the data (Johnson and Albert, 1999) and preference in interpretation (O'Connell, 2006). According to Liao (1994) logit models are more suitable for data distributions with heavier tails.

Clogg and Shihadeh (1994) discusses a variety of ways of forming *"response functions"* for ordinal data which result in the development of different models. The choice of response functions, and hence the type of ordinal model, depends on the research problem. Agresti (2002) and Nelder and McCullah (1989) provide extensive details on these models.

In the published civil engineering literature, ordinal regression models are generally referred to as *econometric* models. To date, the application of ordinal regression models to solve civil engineering problems is limited, although the data encountered is predominantly rank-ordered. For example, FHWA (1995) specifies ten condition grades from 0 (failed condition) to 9 (excellent condition) for condition ratings of bridge decks, and super and sub-structures. Similarly, Pavement Condition Index (a value between 0 to 100 based on multiple pavement distress indicators) is often discretized into 8 rank-ordered categories from 1 representing failed to 8 representing excellent state (Madanat, Mishalani, and Wan Ibrahim, 1995). Baik, Jeong, and Abraham (2006) reviewed the application of ordinal regression models for civil infrastructure deterioration. Baik (2006) found that mostly *ordered probit* models are used for modeling the deterioration of pavement and bridges. Ordered probit and logit models use cumulative probabilities to compute the probabilities of an object *being* in certain internal condition grade depending on covariates. Madanat et al. (1995) and Baik et al. (2006) used ordered probit models based on latent variable formulation to model the deterioration of bridges and wastewater pipelines, respectively. Younis and Knight (2008) developed a partial proportional odds model based on cumulative logits for wastewater pipelines, and Younis and Knight (2009) proposed an ordinal logit model based on generalized linear model formulation.

6.4 Purpose/Problem Statement

This paper presents a new model based on conditional probabilities to compute the probability that a pipe *moves* beyond a condition grade from its current condition.

Furthermore, it also investigates and quantifies the effects of pipe *age* and *material* on the degradation behavior of reinforced concrete and vitrified clay wastewater pipelines.

6.5 Continuation Ratio Model

A Continuation Ratio (CR) model can be obtained from the generalized linear model. Definition of continuation ratio, various types of continuation ratios, and CR model formulation from the generalized linear model is described in the following paragraphs.

Continuation Ratio

The continuation ratio, δ_j, is a "conditional probability that an object moves beyond a stage once a particular stage has been reached, or its complement, the probability that an object does not move beyond a stage once a particular stage has been reached" (O'Connell, 2006). In case of CR models, the response represents a progression of stages such that objects pass through lower stages before they move to higher stages. Thus, for wastewater pipelines, the response i.e., structural Internal Condition Grades (ICGs) of inspected pipes may be considered to represent a direction or sequential mechanism through which pipelines move from lower grades to higher – from good/acceptable condition to bad/collapsed condition.

Types of Continuation Ratios

Different types of continuation ratios – *forward* or *backward* – can be uniquely formed depending on research objectives (Bender and Benner, 2000; O'Connell, 2006). For example, if interest lies in estimating the probability of a pipeline to move to higher/worse internal condition grades provided that it is already in at least that particular condition grade, a forward continuation ratio can be used. However, backward continuation ratio must be used if the objective is to estimate the conditional probability of being in a particular condition grade amongst all objects which are already at or below that condition grade. The forward continuation ratio, $\delta_j(x)$, is represented as (O'Connell, 2006):

$$\delta_j(x) = \Pr(Y > j \mid Y \geq j, X = x) \tag{6.1}$$

where Pr(.) is the conditional probability that response, Y, is greater than a particular condition grade, j, depending on covariates, X.

Or, in terms of complement of Equation 6.1 (Agresti, 2002; O'Connell, 2006):

$$1 - \delta_j(x) = \Pr(Y = j \mid Y \geq j, X = x) \tag{6.2}$$

which gives the conditional probability of staying in condition j.

The backward continuation formulation is given as (Bender and Benner, 2000):

$$\delta_j(x) = \Pr(Y = j \mid Y \leq j, X = x) = \frac{\Pr(Y = j \mid X = x)}{\Pr(Y \leq j \mid X = x)} \tag{6.3}$$

Continuation Ratio Model Formulation from Generalized Linear Model

The generalized linear model is defined as:

$$f\{\pi_j(x)\} = \alpha_j + \beta_j x, \quad j = 1, 2, ..., J-1 \tag{6.4}$$

where f is a link function (logit in the present paper); $\pi_j(x) = \Pr(Y = j \mid X = x)$, i.e., the probability of a response Y being in certain condition grade j depending on covariates X; α_j are the cutpoints for condition grades j; and β_j are the regression coefficients for covariates X.

A Continuation Ratio (CR) model is obtained when the probability, $\pi_j(x)$, in Equation 6.4 is replaced with continuation ratio, $\delta_j(x)$ (Agresti, 2002). That is a CR model is given as:

$$f\{\delta_j(x)\} = \alpha_j + \beta_j x, \quad j = 1, \ldots, J-1 \tag{6.5}$$

Different types of link functions, f, such as *logit*, *probit* and *complimentary log-log* may be employed to describe the relation between response and predictors. For example, in case of a logit link, i.e., $f\{\pi_j(x)\} = \log\{\pi_j(x)/(1-\pi_j(x))\}$, Equation 6.5 becomes:

$$\log\left\{\frac{\delta_j(x)}{1-\delta_j(x)}\right\} = \alpha_j + \beta_j x \tag{6.6}$$

$$\delta_j(x) = \frac{\exp(\alpha_j + \beta_j x)}{1-\exp(\alpha_j + \beta_j x)} \tag{6.7}$$

$$\delta_j(x) = \frac{\exp(\alpha_j + \beta_j x)}{1-\exp(\alpha_j + \beta_j x)}$$

Similarly, when a complementary log-log link, $f\{\pi_j(x)\} = \log\{-\log(1-\pi_j(x))\}$, is used, the following continuation ratio model results from Equation 6.5:

$$\log\left\{-\log\left(1-\pi_j\left(x\right)\right)\right\}=\alpha_j+\beta_j x \quad (6.8)$$

$$\delta_j\left(x\right)=1-\exp\left\{-\exp\left(\alpha_j+\beta_j x\right)\right\} \quad (6.9)$$

The marginal probabilities of *being* in certain condition grade represented as, $\pi_j\left(x\right)$, can be determined using (O'Connell 2006):

$$\pi_j\left(x\right)=\left[1-\delta_j\left(x\right)\right]\left[1-\gamma_{j-1}\left(x\right)\right] \quad (6.10)$$

where $\pi_j\left(x\right)=\Pr\left(Y=j\mid X=x\right)$, $\delta_j\left(x\right)$ is the continuation ratio given by Equation 6.1, and $\gamma_j\left(x\right)$ is the cumulative probability given as $\Pr\left(Y\leq j\mid X=x\right)$.

6.5.1 Estimation

Data Restructuring

To develop a Continuation Ratio Model (CRM), original dataset needs to be restructured such that at each particular stage (i.e., Internal Condition Grades (ICG) in case of pipelines) the objects that fail to make it to the stage are excluded. For a response variable with J ordered categories, there will be a nested set of $J-1$ dichotomies. A dummy variable for each object indicates whether or not that object advanced to the next stage. Table 6.1 and Figure 6.1 show separate nested binary models derived from polytomous response having $J=5$ categories. M1, M2, M3, and M4 represent the continuation of pipelines from grade 1 through 5. For model M1, a dummy variable $Y1$ is included such that $Y1=0$ if the response, ICG, is in $j=1$, and $Y1=1$, if the response is in $j>1$. For model M2, all the observations where $Y1 = 0$ are deleted, and another dummy variable $Y2$ is added such that $Y2 = 0$ if response is in $j = 2$, and $Y2 = 1$ for $j > 2$. This process is repeated until $j = J$. Continuation ratios, δ_j, can then be calculated either through the sequence of binary regression models (M1 to M4), or through a single model that may be developed on the concatenated restructured dataset – provided the slopes are homogenous across separate nested binary models.

Table 6.1: Category Comparison for CR Model for Five Grades

Sr. No.	**Continuation Ratios,** $\Pr(Y > j \mid Y \geq j)$
M1	Categories 2 through 5 vs. category 1
M2	Categories 3 through 5 vs. category 2
M3	Categories 4 and 5 vs. category 3
M4	Category 5 vs. category 4

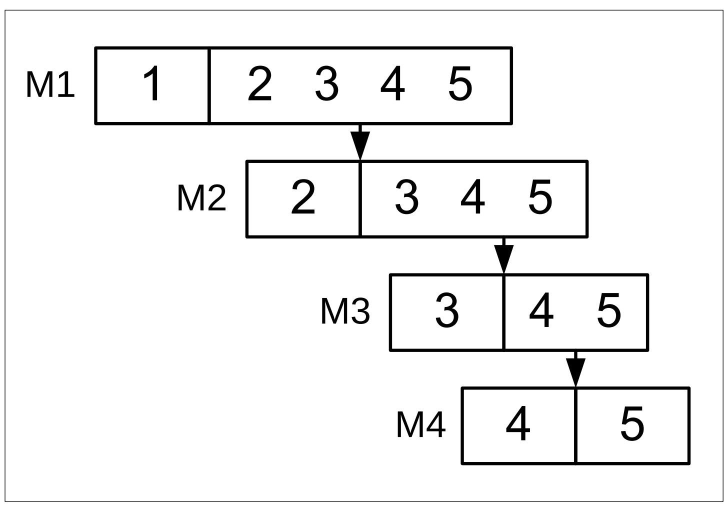

Figure 6.1: Nested Dichotomies

6.5.2 Assumptions

This section presents two assumptions related to ordinal regression models. The methodologies to verify these assumptions are discussed in the validation section.

1. According to Long (1997), the mere fact that a response variable can be written in an ordered form is not a justification for using ordinal modeling techniques. To use ordinal regression models, Long (1997) and Harrell (2001) suggest to check the ordinality of response variable with respect to continuous predictors before starting an analysis. If this assumption is violated, other models such as multinomial logit should be considered.

2. The simplest continuation ratio model – fully constrained CR model – assumes that the slope coefficients, β, are equal for all the computed conditional probabilities across category cutpoints, α_j. That is, $\beta_j = \beta$ for $j = 1, 2, ..., J-1$. Thus, Equation 6.5 becomes:

$$f\left\{\delta_j\left(x\right)\right\} = \alpha_j + \beta x, \quad j = 1, ..., J-1 \tag{6.11}$$

If the assumption of parallel slopes is not satisfied, extended CR model (Harrell, 2001) should be employed.

6.5.3 Validation

Validation involves the verification of model assumptions, as well as, assessing the fit of the continuation ratio model.

Assumptions Verification

Harrell (2001) discussed different strategies to check the Continuation Ratio (CR) model assumptions. For example, to verify the ordinality of response variable i.e., Internal Condition Grades (ICG), with respect to the continuous predictor, *age*, a simple graphical technique may be employed. This requires development of a plot between response and predictor's stratified mean values. That is, the average age of pipes in each ICG is plotted against the ICG. A monotonic relation confirms that the ordinality assumption holds well for the predictor.

To check the assumption of parallel slopes, interaction terms between the category cutpoints and predictors are included in the model. If the assumption of parallel slopes is true, the inclusion of interaction terms between categories cutpoints and predictors will not improve the fit of the model. A significant interaction effect, however, suggests that the effect of a particular predictor is not homogenous across categories, and a more complex model – extended CR – should be considered.

Assessment of Model Fit

Overall model fit can be assessed using the *likelihood-ratio chi-square* test which compares the likelihoods of null (i.e., intercept only) and fitted/proposed models (Long, 1997). If M_β and M_α represent proposed and null models, respectively, likelihood ratio chi-square statistics represented as $G^2\left(M_\beta\right)$, is defined as (Long, 1997) :

$$G^2\left(M_\beta\right) = 2\ln L\left(M_\beta\right) - 2\ln L\left(M_\alpha\right)$$

where $L\left(M_\beta\right)$ and $L\left(M_\alpha\right)$ are likelihood values of proposed and null models, respectively. If the null hypothesis is true (i.e., all β are 0 in model M_β), $G^2\left(M_\beta\right)$ have chi-square distribution with degrees of freedom equal to the number of parameters in the proposed model.

To assess how well the proposed model reproduces observed data, estimated conditional probabilities from the model are compared with the observed conditional probabilities.

6.6 Case Study

To test the proposed model, City of Niagara Falls wastewater pipeline condition assessment data collected by the authors is used. The City of Niagara Falls data is unique as condition surveys are carried out using Side Scanner and Evaluation Technology (SSET). Demonstrated advantages of SSET over traditional CCTV pipeline inspection technologies include the ability to: (1) complete defect rating after the survey is completed; (2) measure pipeline defect changes over time; and (3) more accurately code pipeline defects. Chae et al. (2003) and Knight et al. (2009) present a good discussion on the advantages of SSET over traditional CCTV inspection surveys.

6.6.1 City of Niagara Falls Pipeline Condition Assessment Data

To ensure that a high quality SSET pipeline condition assessment database is developed for the City of Niagara Falls wastewater network, the data collection and data analysis procedure shown in Figure 6.2 is implemented. A contractor supplied North American Association of Pipelines Inspectors (NAAPI) certified operator completed all SSET pipeline surveys, and coded all pipeline defects in accordance with the Manual of Sewer Condition Classification 3rd edition (WRc, 1993). Using NAAPI certified City of Niagara Falls personnel, a second Quality Assurance (QA) and Quality Control (QC) check is performed on all the contractor provided data.

All of the City of Niagara Falls quality pipeline inspection data is transported to the University of Waterloo to be stored on two geographically distributed data servers that are backed up using RAID 5 technology to ensure data security, availability, and seamless recovery. Using a University of Waterloo custom built software application, the City of Niagara Falls QA/QC data is uploaded into a database management system named WatBAMS (Waterloo – Buried Asset Management System). The software import utility contains further QA/QC protocols to ensure that only high quality data is uploaded in the WatBAMS database for each pipe segment survey. Using WatBAMS programmed routines, each pipeline segment is analyzed in accordance with the Sewerage Rehabilitation Manual 4th edition methodology to determine the corresponding Internal Condition Grade (ICG). WatBAMS also allows for the upload and integration with the City's of Niagara Falls GIS and inventory databases that contain each pipe segment's attributes – asset ID, location, construction date, depth, and material type.

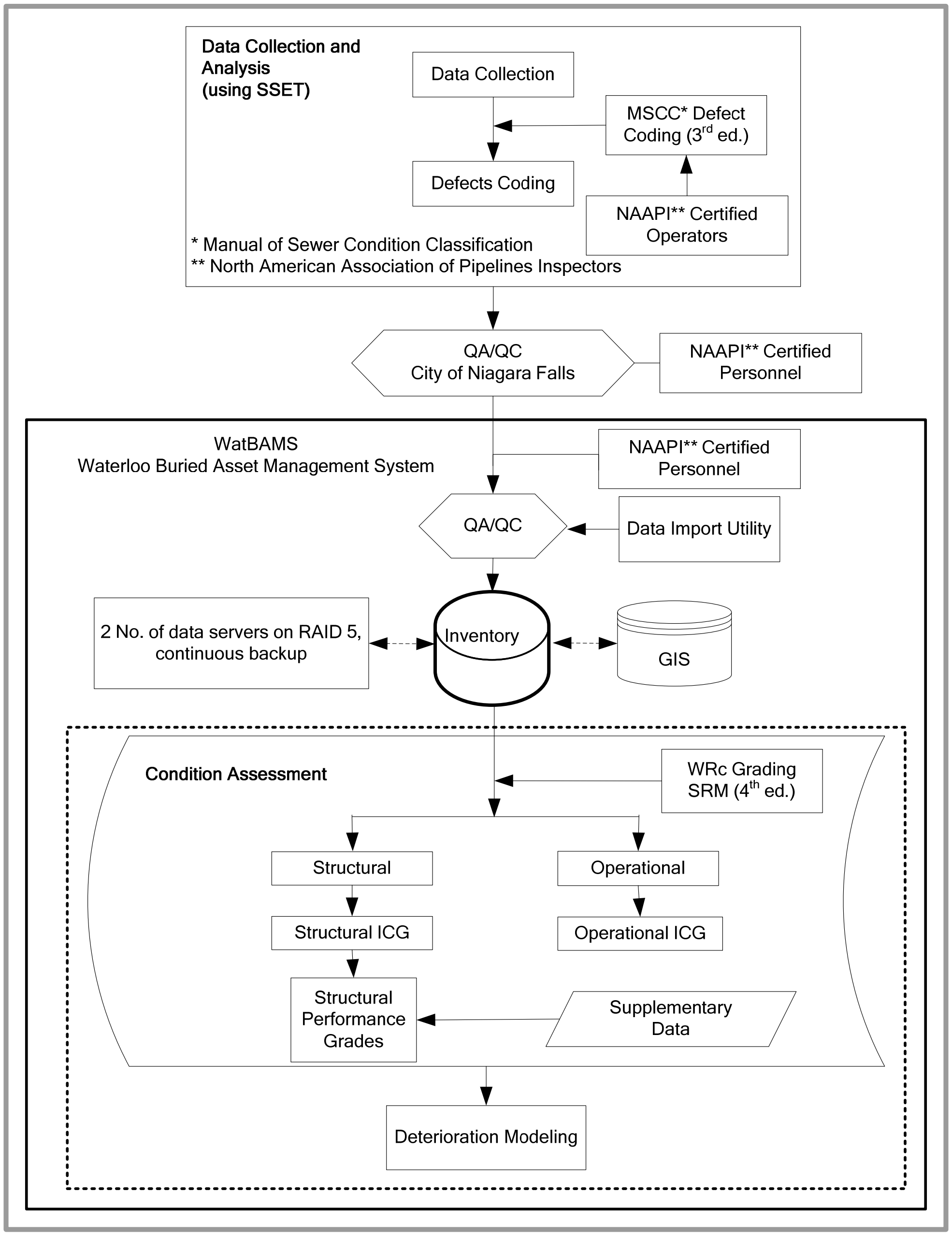

Figure 6.2: Data Collection and Analysis Framework

The City of Niagara Falls wastewater collection network consists of approximately 400 kms of pipelines that has approximately 5,500 pipe segments consisting of a variety of pipe materials with ages that range from over 100 years to less than 20 years with an average age of 47 years. Figure 6.3 shows that 35% of the network consists of Reinforced Concrete (RC), 17% PVC, 10% Vitrified Clay (VC), 10% Asbestos Cement (AC), and 25% of the network has no assigned pipe material. The average age of the RC and VC pipes are 42 and 65 years, respectively. Review of the SSET surveys and defect reports found that VC pipes have open and displaced joints and service connections that were installed by creating a hole in the clay pipe as shown in Figure 6.4 (a) and (b). Thus, there are holes and cracks where service connections enter into the VC pipes. Figure 6.4 (c) shows an example of good workmanship – a perfect connection for VC pipes. RC pipes were found to be generally in good condition except for locations with some displaced joints and structural defects such as exposed rebars, surface wear and spalling, corrosion, cracks, fractures, and broken segments. RC pipes were found to have evidence of hydrogen sulphide and rebar corrosion. Figure 6.4 (d) shows an example of RC pipe with exposed reinforcement due to predisposed corrosion.

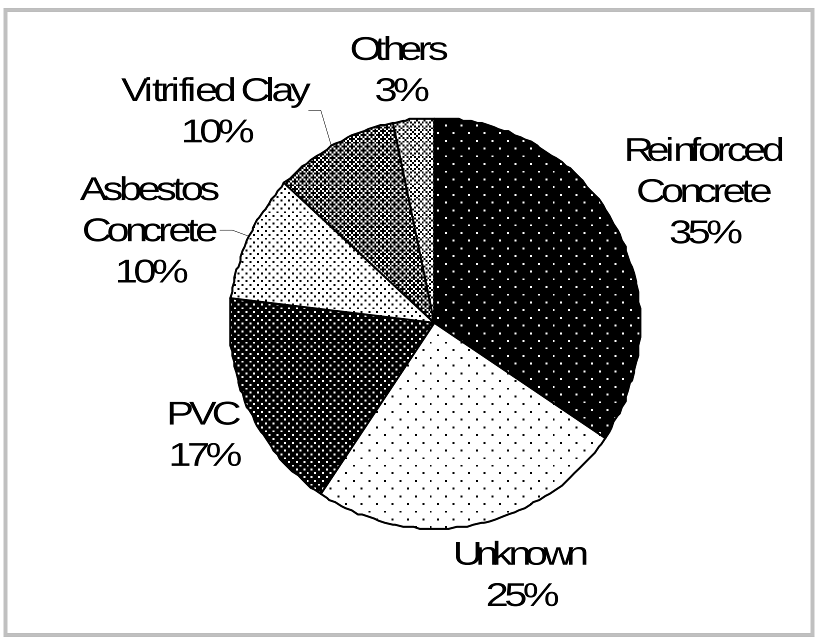

Figure 6.3: Distribution of Various Pipe Materials - City of Niagara Falls Sewer System

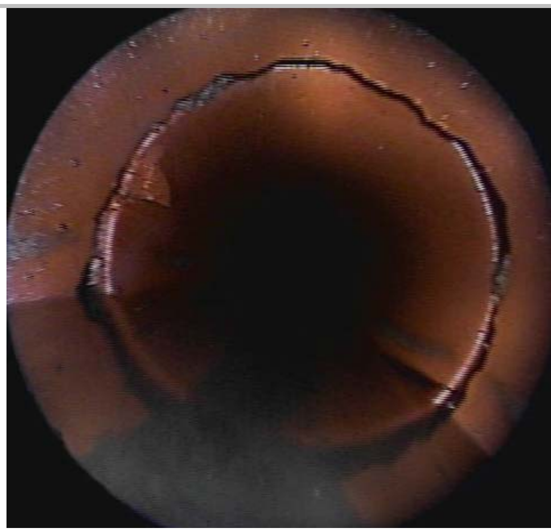

Figure 6.4(a): Open and Defective Joint – VC Pipe

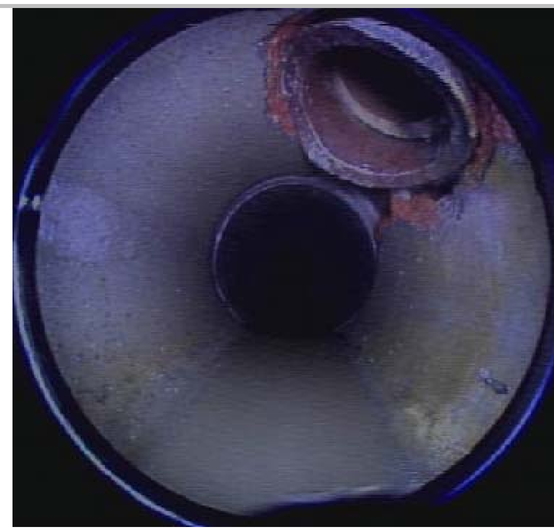

Figure 6.4(b): Defective Connection – VC Pipe

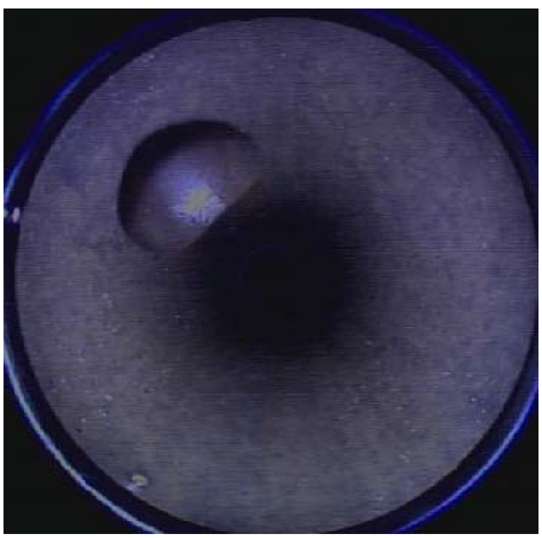

Figure 6.4(c): Perfect Connection – VC Pipe

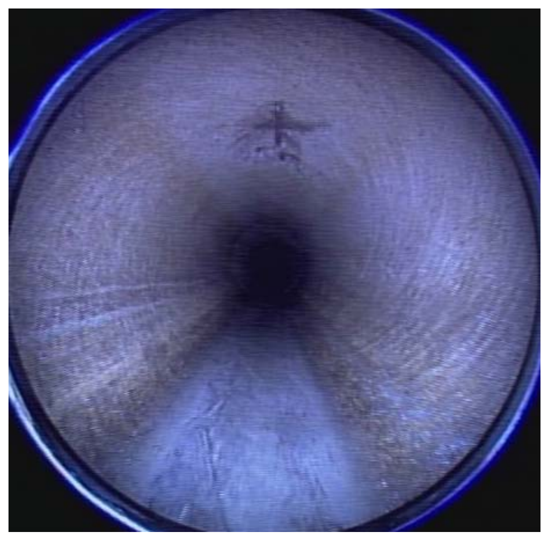

Figure 6.4(d): Exposed Reinforcement – RC Pipe

In the following sections, approximately 12% (45 km) of the City of Niagara Falls wastewater collection network data (collected through stratified sampling) is used to demonstrate the application of the proposed model. The model building process involves checking the ordinality of response variable. Once the ordinality assumption is satisfied, the estimates for model parameters are determined and their statistical significance is checked. Then model validation is carried out by: (1) checking the parallel slopes assumption, (2) goodness-of-fit test, and (3) comparing observed and predicted conditional probabilities. This is followed by interpretation of results and conclusions.

6.6.2 Verification of Ordinality Assumption

Figure 6.5 shows the plot between Internal Condition Grades (ICG) and the average age of pipes in each grade. From the monotonic increasing trend it evident that ICG acts in an ordinal manner with *age*, and ordinality assumption is plausible.

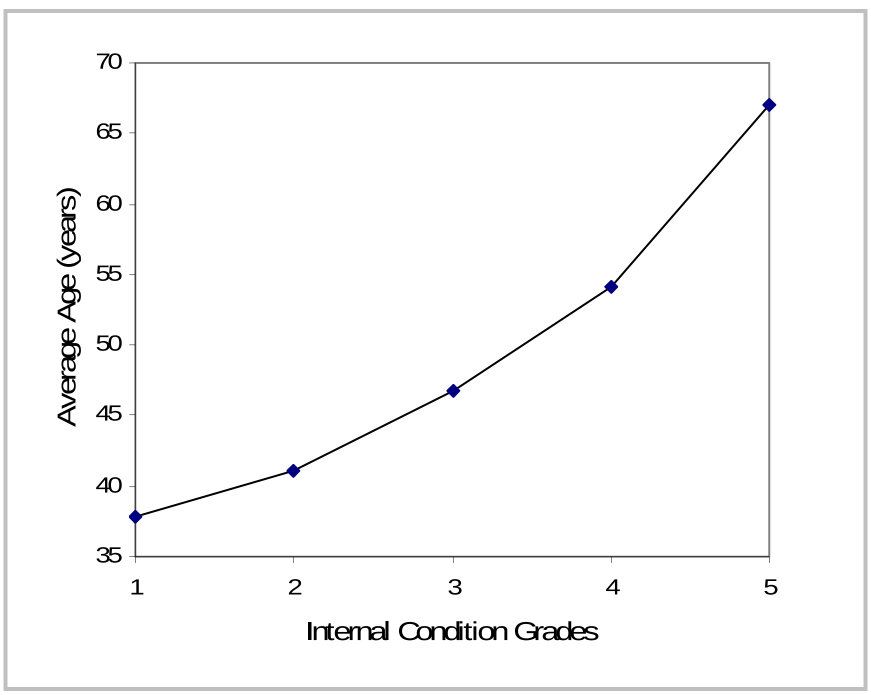

Figure 6.5: Ordinality of Response with age

6.6.3 Model Parameter Estimates

A series of continuation ratio models are evaluated to systematically include and analyze the covariates *material, age*, and their interaction $age \times material$. The results are presented in Table 6.2, where Model 1 contains the pipe *material* predictor only; Model 2 contains pipe *age* and *material*; and Model 3 contains the pipe *age* and *material* along with the term $age \times material$ representing the interaction between the two predictors. The estimates for $(J-1)$ cutoffs, α_j, are shown for Model 3 only. The change in deviance (or likelihood ratio test) statistic, *G,* along with corresponding *p*-value is also provided in Table 6.2 to compare the models.

The estimate for *material* predictor changed from -1.453 in Model 1 to -0.966 in Model 2, a change of 50.4%. This large change in parameter estimate for pipe *material* when *age* is added to the model suggests a strong association of *age* with the response. The average *age* for VC and RC pipes in the sample is 67 and 37 years, respectively. This difference in average *age* for the two pipe materials also contributed to the change in parameter values for the *material* predictor in Models 1 and 2. When Model 2 is compared with Model 1, the likelihood ratio test statistic, *G*, is 25.41 with *p*-value < 0.0001. Since *p*-value is less than 0.05, the change in deviance is significant, and therefore, Model 2 is considered better than Model 1.

To determine the effect of *age* on the response variable for the two pipe materials, Model 3 contains the interaction term $age \times material$ in addition to *age* and *material* predictors. In Model 3, it is interesting to note that the coefficient of *age*, $\hat{\beta}_2$, becomes non-significant as *p*

= 0.248 is greater than the generally accepted statistical significance level of 0.05. Using Equation 6.6, Model 3 can be developed as:

$$\text{logit}\left[\hat{P}\left(Y > j \mid Y \geq j, \text{material}, \text{age}, \hat{\alpha}, \hat{\beta}\right)\right] = \hat{\alpha}_j + \hat{\beta}_1 \text{material} + \hat{\beta}_2 \text{age} + \hat{\beta}_3 \text{material} \times \text{age} \quad (6.12)$$

A dummy/indicator variable that equals 0 in case of Vitrified Clay (VC) and 1 for Reinforced Concrete (RC) is used for the *material* predictor. Therefore, for VC pipes, the right hand side of Equation 6.12 reduces to: $\hat{\alpha}_j - \hat{\beta}_2 \text{age}$. The coefficient for age, $\hat{\beta}_2 = 0.006$ for VC pipes is not significant since the *p*-value is greater than 0.05. Thus, *age* is not related to the response for VC pipes. For RC pipes, the right hand side of Equation 6.12 becomes: $\hat{\alpha}_j + \hat{\beta}_1 + \left(\hat{\beta}_2 + \hat{\beta}_3\right) \times age.$ The parameter estimate for *age* for RC pipes is: $\hat{\beta}_2 + \hat{\beta}_3 = .006 + .035 = .041.$ The significance of $(\hat{\beta}_2 + \hat{\beta}_3)$ is tested using the method of contrasts (Hosmer, 1999) which results in Wald statistic, $z = 5.64$ with *p*-value less than 0.0001, which is significant. Therefore, *age* is found to be related to the response for RC pipes. When Model 3 is compared with Model 2, the likelihood ratio test statistic, $G = 17$ with *p*-value less than 0.0001. Since the *p*-value is less than 0.05, Model 3 is determined to be statistically better than Model 2.

Table 6.2: Continuation Ratio Model (logit link) - Parameter Estimates

Model	Parameter	Estimate	Std. Error	Chi-Square	Pr > Chi-Sq	*G*	*p*-value
1	*mat*, β_1	-1.453	0.194	56.000	<.0001		
2	*mat*, β_1	-0.966	0.216	20.059	<.0001	25.408	<0.0001
	age, β_2	0.020	0.004	23.495	<.0001		
3	Intercept	-0.215	0.436	0.244	0.622	17.000	<0.0001
	Cutoff1, α_1	0.759	0.270	7.884	0.005		
	Cutoff2, α_2	2.539	0.342	55.213	<.0001		
	Cutoff3, α_3	1.755	0.324	29.351	<.0001		
	age, β_1	0.006	0.005	1.333	0.248		
	mat, β_2	-2.731	0.495	30.396	<.0001		
	$age \times mat, \beta_3$	0.035	0.009	15.581	<.0001		

Figure 6.6 and Figure 6.7 show plots of predicted conditional probabilities for RC and VC pipes, respectively. It is evident that the conditional probabilities of advancing to worse internal condition grades are increasing with age for RC pipes, whereas the increase is insignificant for VC pipes. These plots are further discussed in the discussion section. Figure 6.8 shows the probabilities of *being* in certain internal condition grade depending on *age* for RC pipes. These probabilities are computed from predicted conditional probabilities given by CR model using Equation 6.10. The probabilities of being in ICG 1 and ICG 5 are monotonic functions of *age*, whereas, the probabilities of the intermediate categories (i.e., ICG = 2, 3, and 4) are unimodal or single-peaked functions. Thus, the effect of *age* on the probability of being in ICG 1 is negative i.e., the probability of a pipeline being in acceptable condition

decreases with *age* of pipe. On the other hand, the effect of *age* on probability of being in ICG 5 is positive, i.e., probability of a pipeline being in ICG 5 increases with *age*. The predicted probabilities of being in intermediate grades first increase with *age*, and then decrease after certain *age* thresholds. For example, for RC pipes, the probability of being in ICG 3 first increases until the age of about 55 years, and then decreases. This occurs because as the age increases, more pipes move into ICG 3 than leave from ICG 3 to other worse categories. Therefore, the probability of being in ICG 3 increases. As the age is increased beyond 55 years, cases entering ICG 3 are less than the cases leaving, thus the probability decreases. Based on our analysis, the probabilities of being in ICG 5 (collapsed or collapse imminent) for RC pipes exceed the probabilities of being in lower grades at about 75 years for the sample data collected from the City of Niagara Falls wastewater collection system.

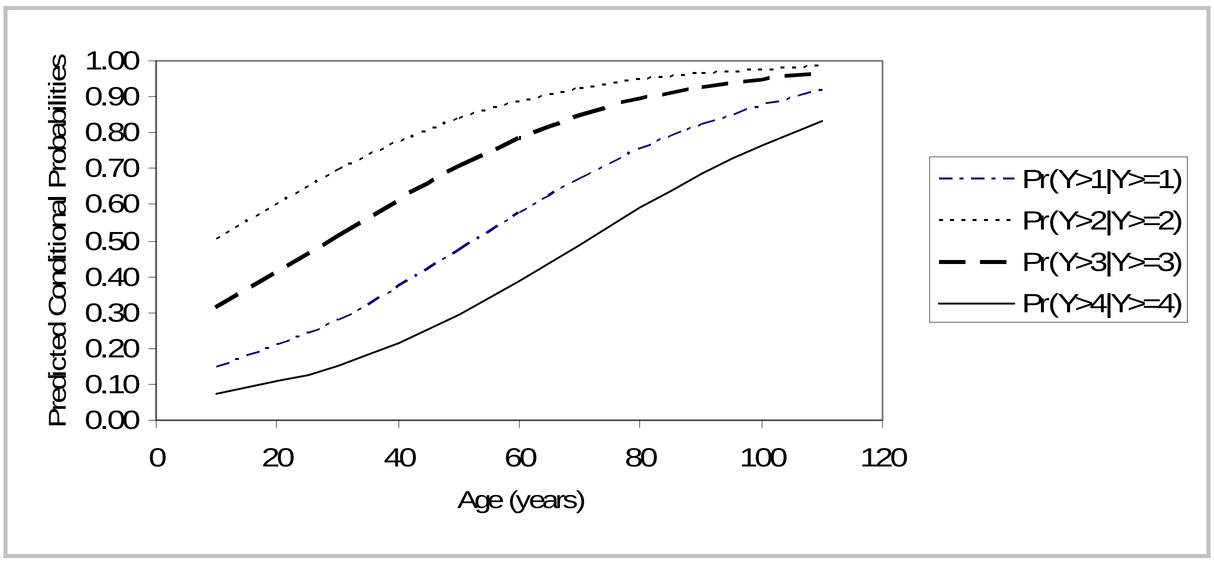

Figure 6.6: Predicted Conditional Probabilities for RC Pipes

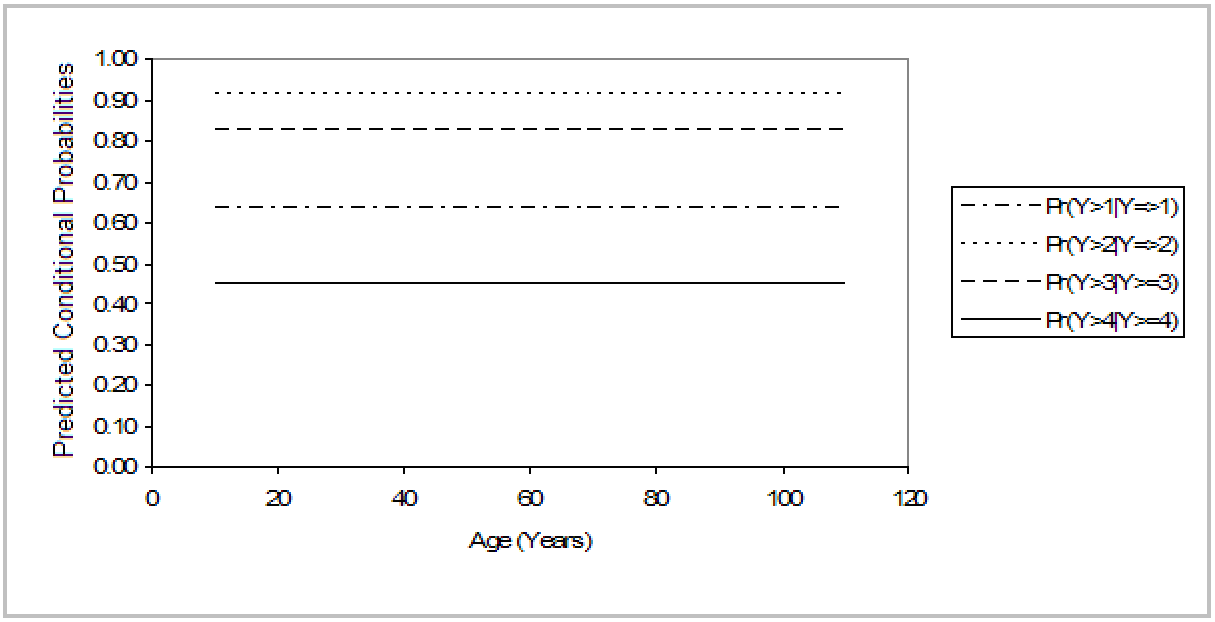

Figure 6.7: Predicted Conditional Probabilities for VC Pipes

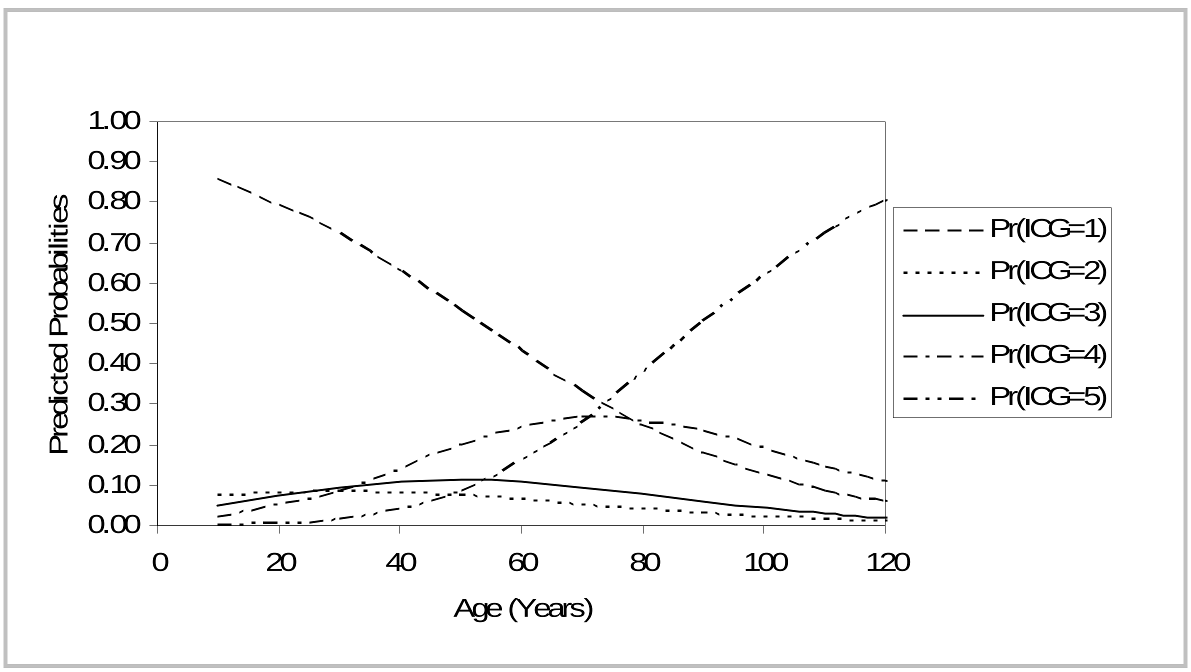

Figure 6.8: Predicted Probabilities of Being in Different ICG for RC Pipes

6.6.4 Model Validation

Checking Parallel Slopes Assumption

The model applied to the City of Niagara Falls data is fully constrained, i.e., it assumes the same effects, β, for each logit. To test this assumption, interaction terms between covariates: *age; material; age*$\times$*material,* and the continuation ratio cutpoints, $\alpha_j, j = 1,..., J-1$ are added. The resulting *interaction* model (calculations not shown) is compared with Model 3 using likelihood-ratio chi-square test. The likelihood-ratio chi-square test statistics, $G^2(M_3)$, is given as:

$$G^2(M_3) = 2\ln L(M_3) - 2\ln L(M_{\text{interaction}})$$

where $L(M_3)$ and $L(M_{\text{interaction}})$ are likelihood values of Model 3 and interaction model, respectively. $G^2(M_3) = 16.202,$ with corresponding *p*-value of $\Pr(\chi^2(9) \geq 16.202) = 0.063$ for 9 degree of freedom. Since the *p*-value is greater than 0.05, Model 4 is not significantly different from Model 3. Therefore, the assumption of parallel slopes, i.e., $\beta_j = \beta$ is considered plausible.

Goodness-of-fit Test

To test the overall model fit, the likelihood-ratio chi-square test statistics, $G^2(M_3) = 2\ln L(M_3) - 2\ln L(M_{null})$ is computed. $G^2(M_3) = 204,$ with corresponding *p*-

value of $\Pr\left(\chi^2(7) \geq 204\right) < 0.0001$. This is significant, as *p*-value is less than 0.05. This shows that the hypothesized model reproduces the data better than the null model.

Observed and Predicted Conditional Probabilities

Table 6.3 shows the comparison between estimated conditional probabilities from the proposed model i.e., $\hat{\delta}_j(x) = \hat{\Pr}(Y > j \mid Y \geq j, X = x)$ and the observed conditional probabilities $\delta_j(x)$ for Reinforced Concrete pipes for average age of 30 and 50 years. The predictions from the proposed model are close to the observed conditional probabilities. This confirms that the model reasonably replicates the observed proportions.

Table 6.3: Observed Frequency, Conditional Probabilities, and Estimated Conditional Probabilities for RC Pipes

age (years)	**ICG**	**1**	**2**	**3**	**4**	**5**
30	Frequency	131	13	13	18	3
	Observed Proportion, δ_j	0.2640	0.7234	0.6176	0.1429	-
	Estimated Proportion, $\hat{\delta}_j$	0.2794	0.6970	0.6675	0.1537	-
50	Frequency	24	8	7	8	5
	Observed Proportion, δ_j	0.5385	0.7143	0.6500	0.3846	-
	Estimated Proportion, $\hat{\delta}_j$	0.4700	0.8403	0.7060	0.2934	-

6.6.5 Discussion

The results presented in this paper are based on our analysis of a sample of condition assessment data from the City of Niagara Falls wastewater collection system. The data was captured using Side Scanner Evaluation Technology (SSET) and defect coded using the 3rd edition of WRc's Manual of Sewer Condition Classification by NAAPI certified operators and analysts. The pipelines' condition is assessed using defect scores from the 4th edition of WRc's Sewerage Rehabilitation Manual using a custom built non-proprietary software application, WatBAMS, developed by the authors.

The presented analysis shows that the degradation behavior of Reinforced Concrete (RC) and Vitrified Clay (VC) pipes is different. For RC pipes, the degradation is found to be age related. The conditional probabilities of advancing beyond a particular Internal Condition Grade (ICG) – to worse condition – from a given ICG increase with age for RC pipes. For example, Figure 6.6 shows that the probability of moving to a worse condition grade from ICG 3 is 60% at 40 years of age, whereas this probability increases to 90% at about 80 years. Since RC pipes are prone to corrosion due to hydrogen sulfide and moisture in addition to other reactive agents in domestic sewage, material loss and deterioration will occur over time. Thus, this finding for RC pipes is deemed reasonable.

The degradation of Vitrified Clay (VC) pipes is found *not* to be age dependent. Figure 6.7 shows that there is no significant change in conditional probabilities with age. Comparing Figure 6.6 and Figure 6.7, it is evident that the conditional probabilities of advancing to worse internal condition grades from a particular internal condition grade are higher for VC pipes up to 65 years of age as compared to RC pipes. For example, at age 40, the conditional probability of advancing to worse condition grades from ICG 1 is about 0.38 for RC pipes (refer to Figure 6.6) and 0.63 for VC pipes (refer to Figure 6.7). However, the probability has increased to about 0.89 at age 80 for RC pipes, whereas there is no appreciable change in probability for VC pipes. The higher probabilities for VC pipes up to 65 years of age as compared to RC pipes may be attributed to poor installation practices as the majority of the inspected VC pipes in the system were found to have open and displaced joints. Furthermore, laterals' connections were found to be defective which could result in cracks, fractures, and holes in VC pipes. These defects due to poor workmanship pushed the VC pipes in worse internal condition grades at earlier age as compared to RC pipes. However, VC, being inert material, is not prone to hydrogen sulphide or corrosion attack, and therefore, does not degrade with age.

Figure 6.6 also shows that the conditional probabilities of advancing to worse internal condition grades from ICG 2 and ICG 3 vary from 0.50 to 0.98 and 0.32 to 0.96, respectively. Whereas, the conditional probabilities of advancing to worse internal condition grades from ICG 1 and ICG 4 vary from 0.15 to 0.92 and 0.07 to 0.83, respectively. The high probabilities of *advancing* from ICG 2 and 3 are attributable to low probabilities of *being* in ICG 2 and 3 for the sampled pipes – the probabilities of being in ICG 2 and ICG 3 are below 0.1 (refer to Figure 6.8).

The presented results are consistent with (Younis and Knight, 2009) which found that the deterioration mechanism for VC and RC pipes is not identical. The results, however, did not support the findings of Ariaratnam et al. (2001); Baik et al. (2006); and Davies et al. (2001) which concluded that the type of pipe material is not a significant factor in deterioration. Davies et al. (2001) used adjacent property age to estimate the age of sewer pipes as they did not have age information of the pipes in their sample. The findings of Davies et al. (2001) are uncertain due to unreliable data for age of pipelines used in their analysis. Davies et al. (2001) and Ariaratnam et al. (2001) used binary logistic regression that did not take into account the ordinal nature of response data. The unconstrained ordered probit model based on latent variable formulation proposed by Baik et al. (2006) was overly complex in terms of number of estimated parameters. This made the interpretation of results quite challenging. The results of our analysis partly confirm the findings of Micevski et al. (2002) which concluded that the type of pipe material affects deterioration. Micevski et al. (2002), however, used multinomial model which did not take into account the rank-ordered information. When different pipe materials have different age distributions, it is important to consider interaction to adjust for age differences, however, all the above cited studies ignored the interaction effect between pipe *age* and *material*.

The estimated conditional probabilities from the presented CR model are used to compute the marginal probabilities of wastewater pipelines *being* in certain internal condition grades depending on pipe *age* and *material*. The conditional probabilities provide the deterioration pattern, whereas the marginal probabilities present the deterioration trend for wastewater pipelines. The marginal probabilities calculated from the CR model using Equation 6.10 are the same as given by the cumulative logit model developed in Younis and Knight (2009). The same dataset was used in the two analyses, and the CR model served as a check on computational accuracy of the cumulative logit model. It is to be noted, however, that direct comparison of parameter estimates from CR and cumulative logit models is not feasible, as both models are inherently different, and estimate different types of probabilities.

6.7 Conclusions

State-of-the-art deterioration models for wastewater pipelines suffer from many shortcomings, such as: (1) models based on expert judgment suffer from bias and validation issues; (2) most of the models do not take into account the ordinal nature of condition assessment data; (3) models are based on inadequate data which was collected with little or no quality assurance and quality control procedures in place; (4) some models are complex in terms of number of parameters to be estimated; (5) models violate assumptions or assumptions could not be verified due to data limitations; and (6) analyses provide limited model interpretations. Therefore, better deterioration models are needed to understand the degradation behavior of wastewater pipelines, and to develop effective and efficient maintenance management plans using reasonable predictions about their condition.

A new deterioration model for wastewater pipelines is developed and applied to the high quality condition assessment data from the City of Niagara Falls wastewater collection system. The model assumptions are checked, and found to be plausible. The model provides valuable information in terms of predicted conditional probabilities of *advancing* to worse internal condition grades from a particular Internal Condition Grade (ICG) for wastewater pipelines depending on pipe *age* and *material*. The continuation ratio model was found to accurately predict the conditional probabilities of advancing beyond an ICG – to worse condition. The Reinforced Concrete (RC) and Vitrified Clay (VC) pipes were found to exhibit different degradation behavior. For RC pipes, the degradation was age dependent, whereas for VC pipes, age was not a factor in deterioration.

The proposed model can be used to establish benchmarks for wastewater pipelines useful service life, predict progression to worse condition states, and determine future rehabilitation and maintenance needs. The model can also be used to develop realistic future maintenance and operation budgets over the life of the asset, and to satisfy regulatory reporting requirements. Further research is required to validate the continuation ratio model in other networks, and to model the deterioration of pipe materials other than RC and VC.

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Chapter 7

Strategic Asset Management Framework for Wastewater Collection Systems Based on Modified Balanced Scorecard Model

This chapter consists of two parts.

Part 1 – up to Section 7.6 – provides an overview of published literature on civil infrastructure asset management frameworks.

Part 2 – starting from Section 7.7 – discusses the new strategic management framework.

7.1 Abstract

This paper presents a strategic planning and management framework to develop, implement, and communicate an integrated asset management plan for wastewater collection networks. New legislative requirements demand increasing accountability to meet stakeholders' expectations, protection of public health and environment, efficient allocation of funds, and greater disclosure. The state-of-the-art civil infrastructure management systems fail to address the gaps between strategy formulation and execution to meet an organization's mandate and mission. The proposed framework takes into account four strategic perspectives – Social/Political, Financial, Operational/Technical, and Regulatory – and devises four strategic themes for sustainable wastewater collection systems. Due to the enormity of the task, and time, space, and data limitations, only the Operational/Technical perspective is discussed in detail.

The asset management strategic themes, perspectives, and objectives presented in this paper are developed on the basis of collaborative working sessions held at the first Canadian National Asset Managers workshop in 2007. The themes and objectives are illustrated in a strategy map and detailed in the modified balanced scorecard model. The use of business intelligence tools to implement, monitor, and report various components of the proposed framework is demonstrated. An example implementation for the City of Niagara Falls wastewater utility is presented. Unlike the existing asset management systems, the proposed system provides a unified gateway to manage wastewater utilities in a timely and effective manner. The proposed framework can be adapted to devise and implement strategic asset management plans in comparable organizations.

Keywords: Wastewater Collection Systems; Strategic Management; Balanced Scorecard; Asset Management; Strategy Maps; Business Intelligence; Sewer Systems.

7.2 Introduction

Urban infrastructure consists of capital intensive physical systems that provide essential services to society such as transportation (pavements and bridges), utilities (water, wastewater, hydro, gas, and telephone), and buildings (offices, health, and education facilities). Wastewater collection networks – an important component of municipal infrastructure systems – are responsible for safe and secure dispose of domestic, industrial, commercial, and public water. It is vital for the utilities – public works departments at municipal or regional level – to maintain and manage these networks for in an effective, efficient, and sustainable manner. Public works departments are accountable with respect to increased public expectations and new government regulatory requirements of protection of public health and environment, efficient use of public funds, and greater disclosure. For example, in Ontario, Canada, *Regulation 453/07 under Safe Drinking Water Act, 2002* (SDWA) (not proclaimed yet) requires that utilities prepare and submit yearly reports regarding current and estimated future condition of water and wastewater infrastructure. Furthermore, to obtain yearly operating licenses from the Ontario Ministry of Environment, utilities must prepare and publish financial plans for long-term sustainability of water and wastewater systems (Ontario Ministry of Environment, 2007). The SDWA also requires municipalities to disclose services quality information to the public. The Canadian Institute of Chartered Accountants Public Sector Accounting Board (PSAB) issued statement PS3150 in 2006 which requires all Canadian municipalities and utilities, starting in January 2009, to report their tangible capital assets along with their depreciation on financial statements (OMBI, 2007). In the United States, the Governmental Accounting Standards Board (GASB)

Statement 34, and in Australia, the Australian Accounting Research Foundation Standard 27 specifies similar accounting practices (FHWA, 2000; Howard et al., 2001).

In Canada, utilities are required to balance their budgets every year (Miller, 2008), and at the same time expected to meet social/political, environmental, operational/technical, and financial obligations. Due to limited revenue, municipalities historically failed to invest in urban infrastructure. This has resulted in a massive infrastructure deficit. The *municipal infrastructure deficit* is an estimate of the total additional investment needed to repair and prevent deterioration in existing, municipally owned infrastructure assets. Estimates of Canada's municipal infrastructure deficit vary from a $44 billion total municipal infrastructure shortfall (TD Economics, 2002) to over $125 billion (Mirza, 2007). Mirza (2007) reports that the infrastructure funding gap for existing water and wastewater systems is $31 billion, and to meet new needs an additional $56.6 billion is required. The size and scope of the infrastructure problems facing municipalities and local governments is enormous as the decay of Canada's infrastructure creates severe domino effects – higher cost of maintenance, operation, rehabilitation, and repair; inefficiency and increased vulnerability; and increased threats to public safety and the environment. Mirza (2007) states that "without maintenance or with deferred maintenance, the municipal infrastructure deficit could be close to $2 trillion by 2065, and that with regular maintenance and good scientific management, the escalating infrastructure deterioration and the resulting infrastructure deficit can be controlled within manageable levels."

The management of wastewater collection pipelines is a challenging issue since wastewater collection systems are usually characterized as 'out of sight, out of mind' (buried underground), and remain virtually untouched and neglected until a failure occurs (Wirahadikusumah et al., 2001). A number of technical guidelines and best management practices have been published to help the municipalities in developing asset management plans to proactively maintain and manage these systems. The majority of these publications and existing practices envisage asset management consisting of the following steps: *data analysis* – provided that necessary data is available, *optimization*, and subsequent *course of actions*. The implementation of the asset management processes is a challenging task due to many constraints such as: lack of knowledge and strategy, lack of tools to implement and execute strategies, financial constraints, human resource issues, lack of understanding of specific legislative requirements, and no single consistent method to measure and communicate performance and educate stakeholders. To address these constraints and to satisfy new regulatory requirements and customer expectations, an integrated strategic management system is required.

The specific objectives of this paper are to: (1) provide a brief overview of the state-of-the-art civil infrastructure asset management literature and practices; (2) present a new strategic management framework for wastewater utilities based on modified balanced scorecard model; (3) describe the application approach and tools for implementing the proposed framework; and (4) illustrate the use of the proposed framework.

7.3 Literature Overview

The need for effective and efficient maintenance management of municipal infrastructure systems, especially wastewater infrastructure, gained substantial prominence in the last decade. As a result, a number of tools such as asset management plans, methodologies, best management practices guidelines, management frameworks, and benchmarking initiatives have been proposed for sustainable municipal infrastructure. This section provides an overview of asset management definition and processes, and reviews some of the prominent published literature on infrastructure management. The section concludes with a discussion on published literature and initiatives, and the need for an improved methodology for implementing strategic asset management practices in water/wastewater utilities.

7.4 Infrastructure/Asset Management

According to Grigg (2003), *Infrastructure Management* is the process of planning, coordinating, and executing civil infrastructure systems over the life-cycle i.e., "from cradle to grave"; whereas *Asset Management* applies financial concepts to infrastructure systems management. Grigg (2003) emphasized that infrastructure management and asset management are one and the same thing.

Asset Management Definition

There are numerous definitions of asset management which are continuously refined with the emergence of the field (FHWA, 1999). US Department of Transportation, Federal Highway Administration (FWHA) suggested the following working definition of asset management:

"Asset management is a systematic process of maintaining, upgrading, and operating physical assets cost-effectively. It combines engineering principles with sound business practices and economic theory, and it provides tools to facilitate a more organized, logical approach to decision-making. Thus, asset management provides a framework for handling both short and long-range planning" (FHWA, 1999).

Essential Technical Elements of Asset Management

Figure 7.1 shows the basic technical elements of an asset management system in terms of seven questions proposed by Gohier (2006). The asset management processes can be divided into three distinct components: (1) inventory: includes a catalog of physical assets and their market value; (2) maintenance management plan: consists of condition assessment, maintenance/rehabilitation/reconstruction strategies and their timelines; and (3) financial plan: deals with money requirements and funding mechanisms.

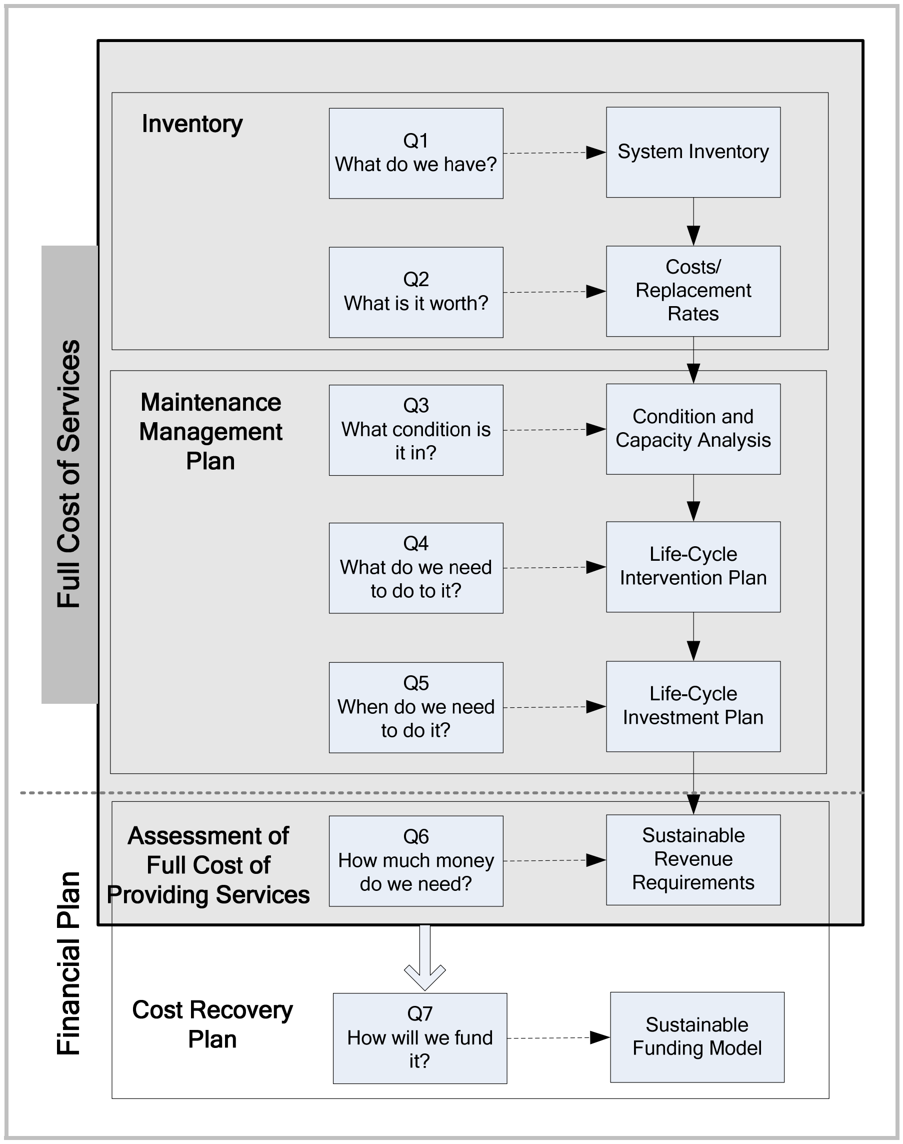

Figure 7.1: Technical Elements of Asset Management (adapted from Gohier, 2006)

There are two levels of maintenance management (Hudson et al., 1997): (1) Network level; and (2) Project level.

Network level management envisages maintenance and rehabilitation decisions regarding the whole network. For wastewater collection systems, it involves prioritization among entire wastewater collection network based on condition assessment, and then optimizing available resources. This essentially translates to knowing the number of pipes in different condition states, their criticality, and devising engineering and economic strategies for capital planning and long-term sustainability.

Project level management refers to maintenance and rehabilitation decisions regarding individual components. In case of wastewater systems, it involves formulating cost-effective maintenance and rehabilitation alternatives for each pipe segment from the available options.

7.5 Infrastructure Management Frameworks

Many publications exist on how to manage civil infrastructure facilities. For example, Hudson et al. (1997) discussed an overall framework for infrastructure management and provided a systematic methodology for infrastructure management. Figure 7.2 shows that Hudson et al. (1997) differentiated between program/network/system-wide and project/section levels management. The main components of their infrastructure management framework include ongoing in-service monitoring and evaluation, and database systems.

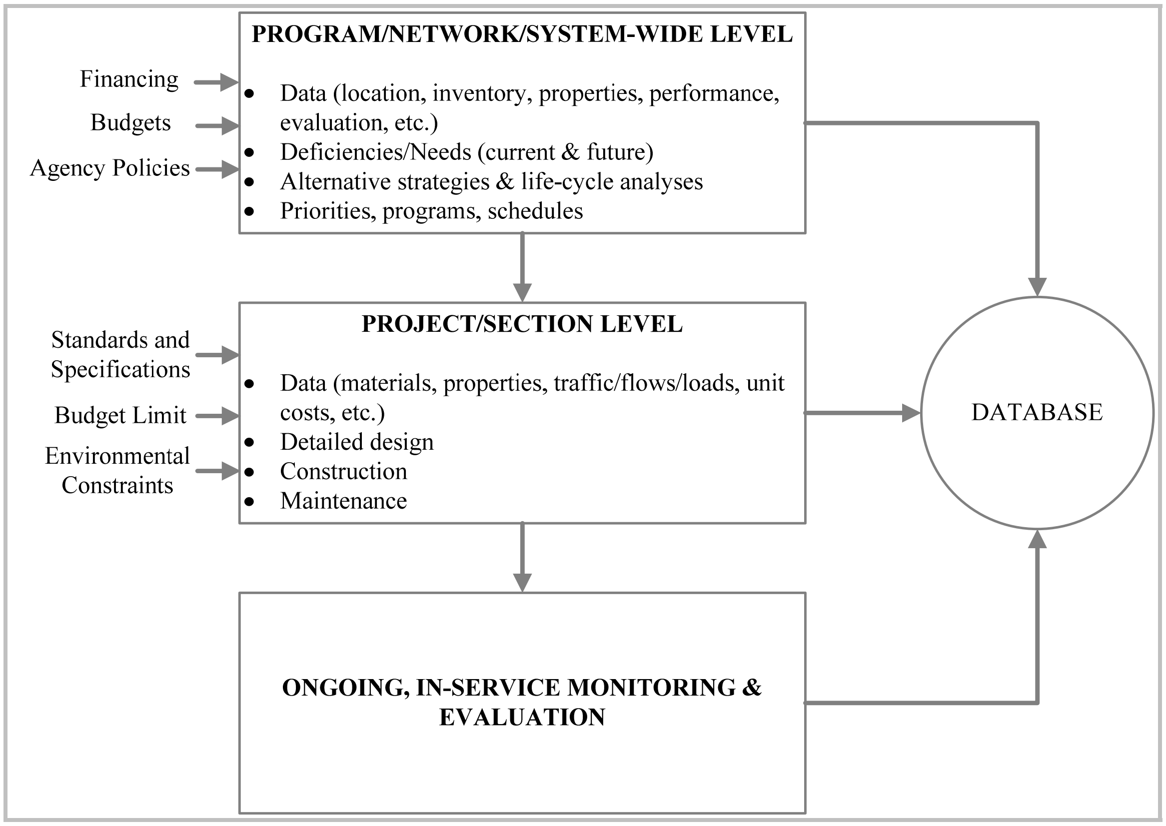

Figure 7.2: Overall Framework for Infrastructure Management (Hudson et al., 1997)

The International Infrastructure Management Manual (IIMM) (NAMS, 2002) details a systematic process for infrastructure management. The two main approaches for developing asset management plans described in IIMM include: (1) basic asset management; and (2) advanced asset management. As shown in Figure 7.3, the basic approach is based on rudimentary data and information to develop asset management plans, whereas, the advanced approach takes into account actual condition assessment data, systems performance, and risks to optimize maintenance, rehabilitation and reconstruction of civil infrastructure facilities.

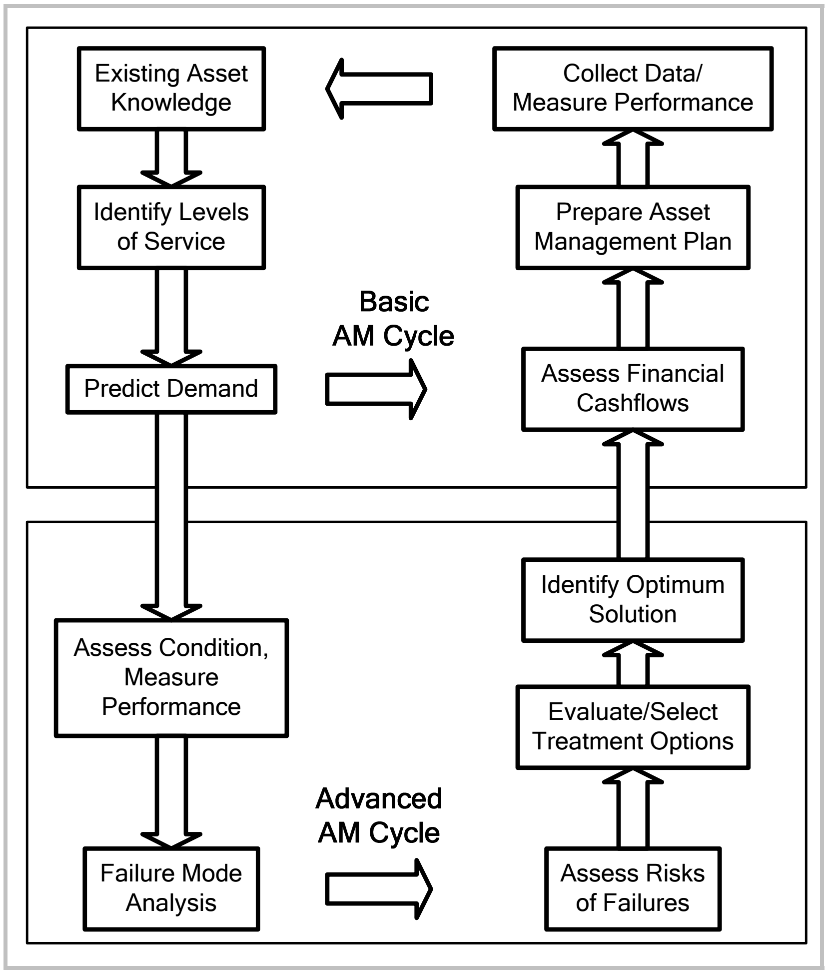

Figure 7.3: Basic and Advanced Asset Management Strategies (adapted from NAMS, 2002)

In Canada, the National Roundtable on Sustainable Infrastructure (NRTSI) proposed a National Asset Management (NAM) Framework (see NAMWG, 2009). Figure 7.4 presents the NAM framework that NRTSI foresee to be the foundation of every asset management activity in Canada. The framework consists of objectives, assessment criteria and performance indicators for core public infrastructure – pavements, bridges, water, wastewater, etc. The framework provides definitions of selected performance indicators but lacks information about how to measure the proposed performance indicators. Furthermore, it also does not provide implementation details.

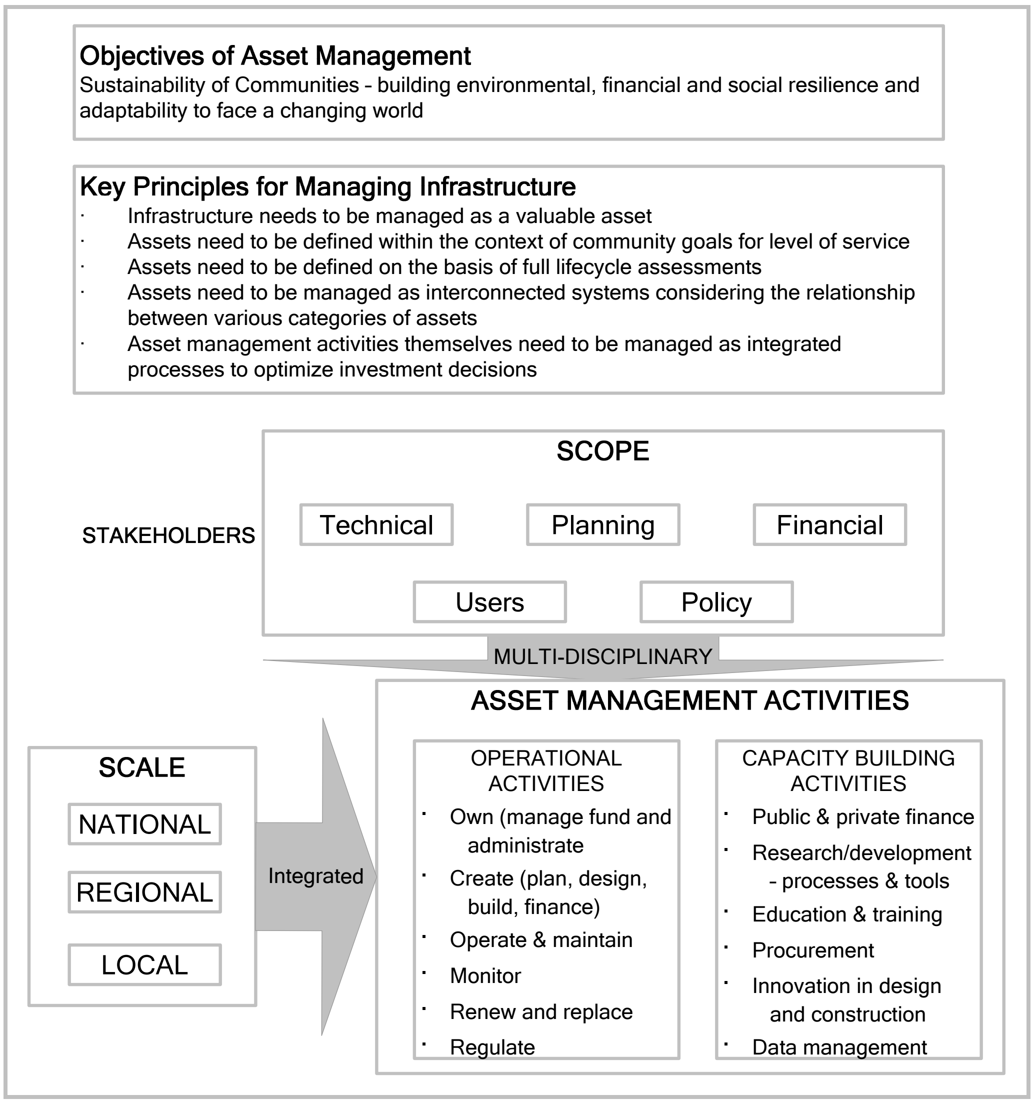

Figure 7.4: National Asset Management Framework (NAMWG, 2009)

7.5.1 Sewerage Rehabilitation Manual

The Sewerage Rehabilitation Manual (SRM), published by Water Research Center in UK, describes a wastewater pipelines renovation decision making process as shown in Figure 7.5. The SRM discusses in detail the techniques for carrying out initial planning and performing diagnostic studies from hydraulic, environmental, structural, and operations viewpoints. It further elaborates the development and implementation of rehabilitation techniques and monitoring systems for wastewater collection networks.

7.5.2 Best Management Practices Guides

A number of guides for best management practices have been published. For example, in Canada, the Federation of Canadian Municipalities, the National Research Council, and Infrastructure Canada produced InfraGuide: The National Guide to Sustainable Infrastructure (FCM & NRC, 2003). InfraGuide is a collection of case studies, best practices reports, and e-learning tools for maintenance management of civil infrastructure facilities in Canada. In the USA, the Environmental Protection Agency published guides such as (1) Asset Management: A Best Practices Guide; (2) Asset Management for Local Officials; and (3) Building an Asset Management Team (U.S. Environmental Protection Agency, 2009). These guides are meant to help asset managers at cities, corporations, and utilities to understand, develop, and implement asset management plans.

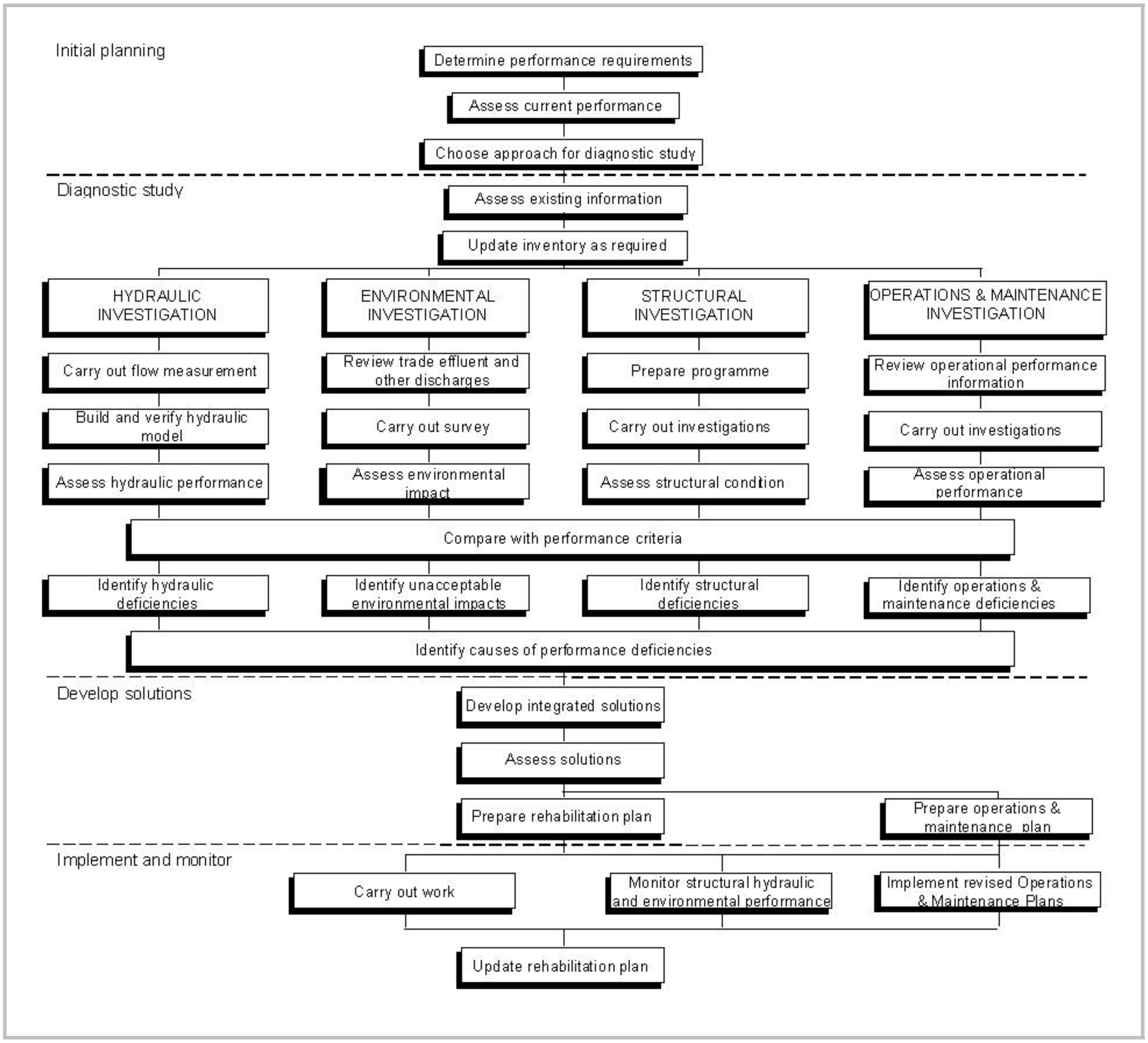

Figure 7.5: Full Investigation Flowchart (WRc, 2001)

7.5.3 Benchmarking Initiatives

Benchmarking is a popular management tool to improve performance by comparing standard processes to that of peer organizations. In Canada, the Ontario Ministry of Local Affairs and

Housing requires all the municipalities to report on efficiency and effectiveness measures for their services under the Municipal Performance Measurement Program (Burke, 2005). The list of measures include elements such as operating costs for governance and corporate management, as well as, for various services – water, wastewater, police, fire, transpiration, libraries etc. For wastewater infrastructure, municipalities are required to provide information on the number of wastewater main backups per 100 kms of wastewater main in a year, and estimated percentage of wastewater that by-passed treatment.

Ontario Municipal Benchmarking Initiative (OMBI, 2008) is a project by Chief Administrative Officers and City Managers from OMBI partner municipalities to identify and develop performance measurements, collect data from partner municipalities, and benchmark the results to identify best management practices. The OMBI project intends to develop an integrated management tool by aggregating financial and performance data to facilitate decision making at the municipalities.

The Canadian National Water and Wastewater Benchmarking Initiative (NWWBI) (Main et al., 2006; NWWBI, 2009) was launched in 1997 to help the participating utilities to manage, monitor, and improve their performance. NWWBI proposed a Utility Management Model with seven goals related to cost minimization, systems reliability and sustainability, infrastructure adequacy, public health and safety, work environment, customers' satisfaction, and environmental protection. For each goal, a number of performance measures are defined for water and wastewater infrastructure. The participating utilities are surveyed annually by NWWBI representatives to collect data on mutually agreed performance measures. NWWBI advocates a *collaborative* approach to benchmarking where the participants learn by sharing performance data rather than the traditional private sector's *competitive* approach where organizations are pitted against each other to be the best on the market.

7.5.4 CARE-S and CARE-W

In 2001 and 2002 the European Commission allocated €8 million for CARE-W (**C**omputer **A**ided **RE**habilitation of **W**ater Networks) (CARE-W, 2008) and CARE-S (**C**omputer **A**ided **RE**habilitation of **S**ewer Networks) (CARE-S, 2008) projects, respectively. The CARE-S project included 15 partners from ten European countries for the development of a decision support system for the management of wastewater collection networks. The final outcome consists of 21 software pieces, 31 reports, and numerous publications. The proposed decision support system was tested at twenty cities (end-users). The proponents of the program *hope* that CARE-S and CARE-W systems will become leading instruments for managing water and wastewater infrastructure in the future (Saegrov, 2006).

7.5.5 Asset Management Software

A number of commercial and proprietary software are available for infrastructure asset management. Halfawy et al. (2006) carried out a review of key features, capabilities, and limitations of some of the most widely used software systems, and concluded that the vast majority of existing software systems mainly focus on operational aspects such as work orders or service requests with little or no functionality for making long-term maintenance and rehabilitation decisions – that is, existing systems offer little help in strategic management. Newton and Vanier (2005) conceded that efficient operations and cost-effective decision-making was not possible with the "Commercial-Off-The-Shelf (COTS)" products.

7.6 Discussion on Current State of Civil Infrastructure Management Practices

Despite of perceived benefits of asset management and reasonable literature on civil infrastructure management, the actual implementation of asset management practices at wastewater utilities is still at an infancy stage. Woodhouse (2009) highlighted the asset management processes as multiple stages of "*temporary enthusiasms*" as shown in Figure 7.6, because majority of the asset management initiatives die down within two years of their inception.

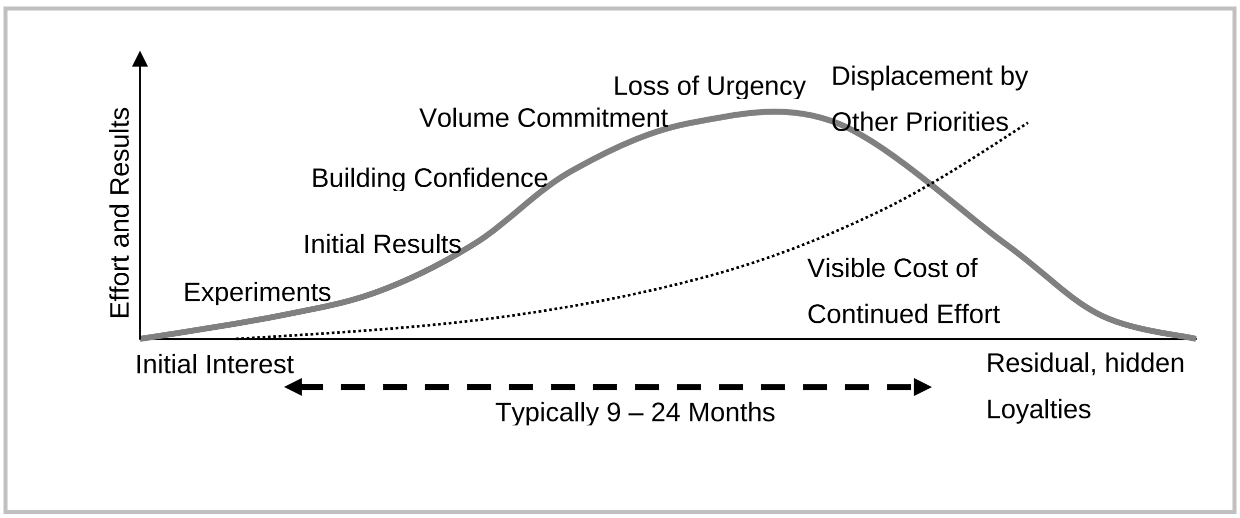

Figure 7.6: Life-Cycle of Asset Management – Temporary Enthusiasms (Woodhouse, 2009)

The frameworks such as NAMS (2002) and Hudson et al. (1997) stipulate mission and objectives statements, and provide details about infrastructure management processes. According to Bain and Company (2009), mission and vision statements are often employed as a management tool to provide an organization's purposes, business goals and values.

Many public and private sector organizations have mission, values, and vision statements, and describe strategies in terms of programs and initiatives to carry out their mission and accomplish their vision. However, strategy implementation is more challenging than strategy formulation. According to Niven (2005), about 90% of organizations fail to execute their strategy due to barriers, such as lack of vision, management, and resources. Despite of a number of proposed asset management systems, plans, frameworks, and on-going initiatives, utilities still struggle to implement and execute their strategies to effectively and efficiently manage civil infrastructure systems. This is evident from periodic surveys (e.g., PricewaterhouseCoopers, 2003) and reports on the status of asset management practices at various municipalities as well as workshop proceedings on asset management challenges (e.g., CNAM, 2009; Frangopol et al., 2003). In 2004, the Ministry of Finance in Ontario, Canada, completed a survey to investigate municipal water and wastewater systems asset management practices. This survey found that among the responding Ontario municipalities, 52% do not perform inspections for condition assessment or record the results of inspections (PricewaterhouseCoopers, 2003). The survey also found that large municipalities – more than 50,000 population – typically have better asset management practices, and asset management approaches ranged from “don’t fix it if it is not broken” strategies to the use of computationally intensive and sophisticated software tools. These surveys demonstrate current state-of-the-art in asset management by municipalities in Canada and most likely in North America.

Municipal benchmarking initiatives can be useful to improve asset management practices if the systems being benchmarked have the same characteristics at participating municipalities or they follow the same business practices. However, benchmarking is not a useful management tool when it is used to compare fundamentally different systems and business processes. For example, different wastewater collection systems can have different age and material distributions for pipelines, and can be operating under different environments and demands. Similarly, the costs to provide services can depend on many localized factors. Performance measures, such as number of pipe breaks or sewer overflow events, provide little information to assess a utility, and mean little to improve the business processes or systems' performance.

The major problem – in addition to resource barrier – is the complexity and lack of understanding in implementing and aligning asset management processes in the overall organizational strategy. The asset management plans – if they exist – are not consistent with strategic plans.

7.7 Proposed Asset Management Framework

This section introduces an integrated strategic asset management framework based on the Balanced Scorecard (BSC) model. The framework provides the essential supporting structure and system for an efficient, effective, and sustainable provision of wastewater collection services. The review of strategic management and traditional BSC model is provided followed by the development of integrated strategic management framework using a modified BSC model. An example framework is discussed to elaborate the application of the proposed framework.

7.7.1 Strategic Management

Strategic management is a continuous process of specifying an organization's mission, vision, and objectives, and developing policies, plans, and initiatives – in terms of projects and programs – designed to achieve organizational objectives. According to Dess et al. (2006), strategic management: (1) directs organizations towards overall goals and objectives; (2) involves multiple stakeholders in decision making; (3) incorporates both short- and long-terms perspectives; and (4) recognizes tradeoffs between efficiency and effectiveness.

Strategic planning, an integral element of strategic management, is the second most widely used management tool – listed as first for 'satisfaction with results' according to the Bain & Company's Top Ten list of most used tools (Rigby and Bilodeau, 2009). Many organizations employ more than one management tools to conduct and manage their businesses. According to Kaplan and Norton (2004), organizations develop mission and vision statements as management tools but fail to translate them into actionable strategies, or their mission and vision are misaligned within the organization (Niven, 2005). The Balanced Scorecard Model has been proven to be an effective tool to develop strategic management systems for private and public sector organizations.

7.7.2 The Balanced Scorecard Model

The Balanced Scorecard (BSC) provides a useful framework for strategic management and corporate governance. The BSC model is a flexible and simple management tool introduced by Kaplan and Norton for coordinating between business organizations' strategic and operational objectives (Kaplan, 1996). BSC was initially developed as a measurement tool to facilitate tracking and measurement of organizations' financial results along with three additional perspectives which include customer, internal business process, and learning and growth. Later on, BSC evolved as a strategic management tool to overcome two of the most serious deficiencies of traditional management systems: (1) failure to link strategy to mission and vision, and (2) failure to execute strategy (Kaplan, 1996; Niven, 2005). Figure 7.7 shows four perspectives of BSC consisting of: (1) financial, (2) customer, (3) internal processes, and (4) learning and growth, as proposed by Kaplan (1996). To implement the BSC model, objectives are assigned to each of the perspectives, and measurements and targets are allocated. Then, actions or initiatives are proposed to achieve the specified targets for each objective.

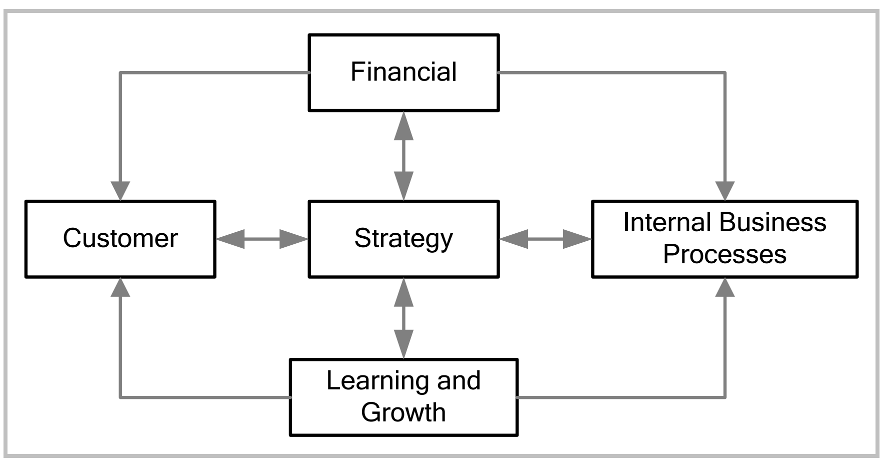

Figure 7.7: The Balanced Scorecard (Niven, 2005)

The BSC model has evolved from performance measurement to strategic management, strategy execution and communication tool. Strategic management using BSC is also known as management by objectives whereby performance measurements are used to provide feedback on internal processes and external outcomes to meet an entity's desired mission and vision. Two main components of BSC model are (Chenoweth and Bird, 2005):

Management Tool consisting of: (1) objectives, (2) Key Performance Indicators (KPIs) – *leading* indicators or measures to assess achievement of objectives, and (3) KPIs – *lagging* indicators consisting of targets and results, and

Management Strategy consisting of action plans or initiatives to achieve objectives.

The proposed integrated strategic wastewater asset management framework modifies and enhances the number and naming of perspectives and objectives in the traditional BSC model and related tools e.g., vision and mission statements; strategy themes and maps etc., – as discussed in Kaplan (1996), Kaplan and Norton (2004), and Niven (2005) – to specifically reflect the objectives, issues, and needs of a typical wastewater utility. The following section describes the proposed framework for wastewater collection networks.

7.8 Strategic Management Framework for Wastewater Collection Networks

The key components of the proposed strategic management framework are shown in Figure 7.8 and defined in Table 7.1. These components are further explained using an example framework provided in Section 7.10. Figure 7.8 shows that the strategic management process starts with defining/reviewing the mission, values, and vision statements of the wastewater utility. Mission, values and vision are required to provide guidance for the organization. Strategic and performance goals and objectives are derived from the mission, values and vision statements. Strategy – consisting of multiple strategic themes – provides an elaborate and systematic plan to accomplish stated mission and vision in terms of objectives. For example, the strategic themes of a wastewater utility may comprise of: (1) ensuring public health and safety; and (2) reducing long-term costs of services. Strategy maps along with the balanced scorecard model are management tools to describe, measure, and communicate strategy. The balanced scorecard initiatives – short and long-term actions/projects – are assessed for financial feasibility, and operating and capital budgets are specified for feasible programs. For unfeasible initiatives, a review may necessitate the revision of mission, values, and vision. An effective communication and feedback mechanism is critical to connect wastewater network internal and external stakeholders.

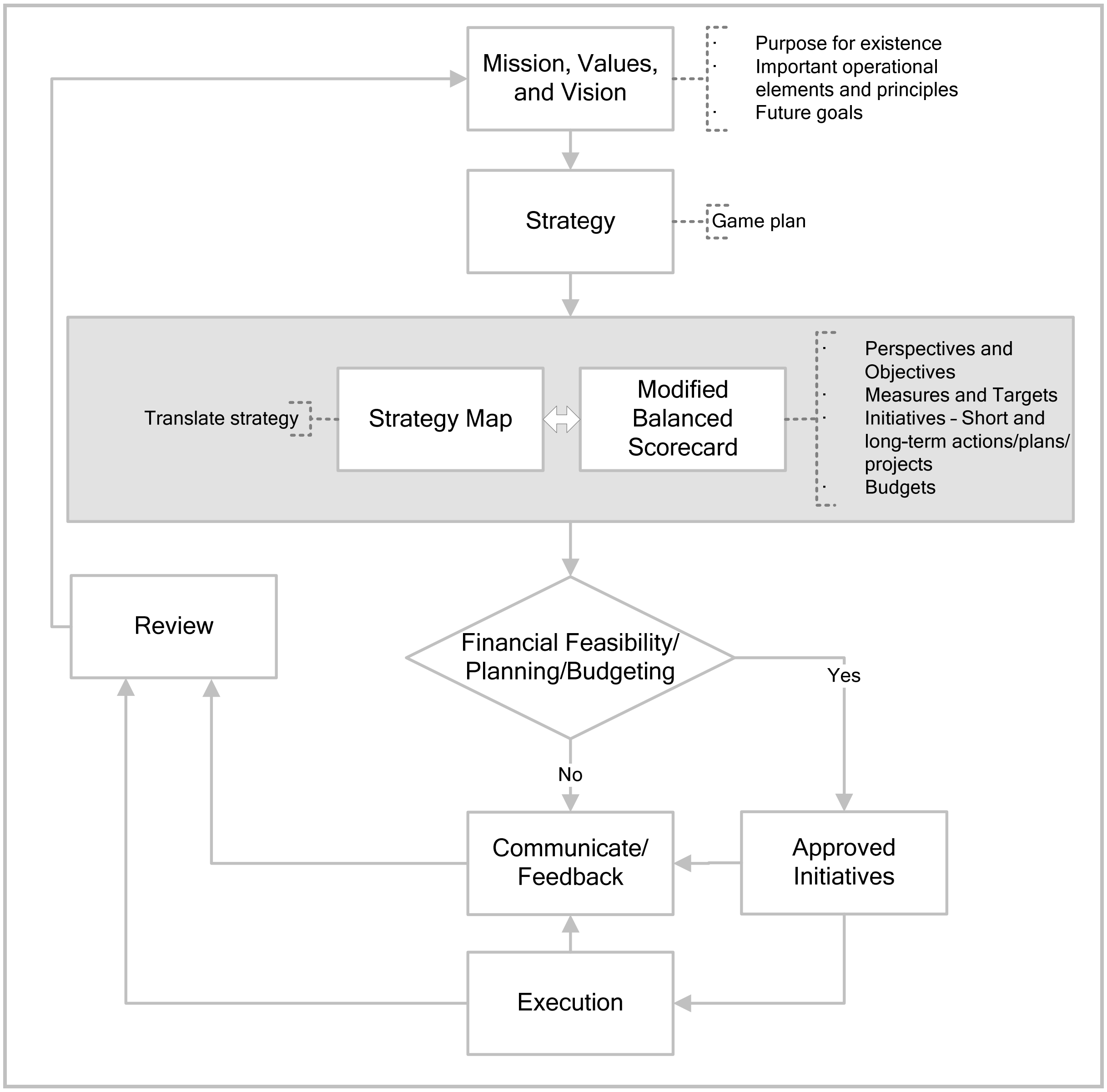

Figure 7.8: Proposed Strategic Management Framework

Table 7.1: Components of Strategic Management Framework (Glossary)

Mission, Values, and Vision
Mission – Basis for existence of an organization. Values – Philosophy and important operational elements and principles. Vision – Long-term goals and objectives.
Strategy
Strategy is the scheme or a systematic plan of action to achieve objectives over the long-term.
Strategy Map
Strategy map communicates organizational objectives and logic of strategy. It is used as a tool to translate strategy into actionable objectives, and to facilitate the link between strategy formulation and strategy execution.
Modified Balanced Scorecard
Balanced scorecard translates strategy map objectives into measures and targets. Balanced scorecard consists of the following key components: *Perspectives* refer to different viewpoints or important elements that define performance. *Measures* are the metrics used to track and evaluate performance on objectives. *Targets* are the desired results of a performance measure. *Initiatives/Actions/Plans* refer to programs and activities to achieve targets.
Financial Planning/Feasibility/Budgeting
This involves assessing the financial feasibility of proposed programs and projects, and allocating resources for feasible initiatives.
Communicate/Feedback
This pertains to involving all the stakeholders into strategic management program by formulating and communicating mission, vision, strategy, initiatives, and strategic outcomes, and getting their feedback.
Review
This involves regular evaluation and audit to ensure that management system is working satisfactorily.

7.9 Modified Balanced Scorecard – Formulation of Perspectives and Objectives

The perspectives and objectives of the proposed balanced scorecard model were developed on the basis of multiple collaborative working sessions held during the first Canadian National Asset Management (CNAM) Workshop held in Hamilton, Ontario, Canada in 2007 (CNAM, 2009). During the CNAM workshop, over 120 experts including representatives from 35 Canadian municipalities, academia, industry, and specialists from Australia and New Zealand, deliberated in focus groups, and discussed and debated asset management challenges and opportunities. The authors – being part of the organizing committee – participated in every aspect of the workshop from organization to compiling and analyzing the findings, and dissemination of results. The deliberations were iterative, and the following steps were implemented.

The participants were divided into four different groups to avoid potential skewness/bias from few dominant members. All the four groups deliberated in isolation from each other under the guidance of skilled and experienced moderators. To ensure maximum participation and to facilitate the free-flowing discussion, all the focus groups were further subdivided into subgroups.

In each focus group, no fixed questions or directions were provided, and all the participants were given freedom to brainstorm and comment on anything they deem important with respect to infrastructure asset management.

All the issues that were brought up by the participants were documented on flip charts. Then, each participant was given fixed number of voting stickers to vote for the issues that they felt important. The participants were free to cast as many votes to a certain issue as they wished according to their own weighing criterion.

The same procedure was repeated for all the four prescribed perspectives – social/political, financial, regulatory, and operational/technical – of municipal infrastructure management.

The issues that received zero votes were dropped out, and the issues that obtained top votes in each of the category were selected as the top priority objectives.

Later, all the groups were convened, and the aggregated results were analyzed and discussed.

Additionally, interviews with infrastructure managers and in-depth review of published literature and current practices were carried out to formulate the objectives in the modified BSC model.

Results

The findings from the workshop were compiled to formulate the modified balanced scorecard as shown in Figure 7.10. From the workshop proceedings and subsequent analysis, the mission of infrastructure providers is defined *to provide safe, secure, and reliable infrastructure to the society*. The vision of infrastructure providers is *to become self-sustainable in the future while providing adequate services to customers at minimum long-term cost*. Four identified strategic themes include: (1) meet regulatory requirements; (2)

provide a reliable and adequate infrastructure; (3) meet stakeholders' expectations; and (4) minimize long-term cost. The four proposed key perspectives for municipal infrastructure management include: (1) social/political; (2) financial; (3) operational/technical; and (4) regulatory. The social/political perspective takes into account the stakeholders – customers, service providers, and governments – to address public safety, environmental protection, and education issues. The objectives in financial perspective include developing long-term financial plans and becoming financially self-sustainable. The regulatory perspective specifies objectives such as to develop a better understanding of regulatory requirements, to comply with regulatory requirements, and to create specifications for consistent reporting. Operational and technical objectives include developing better understanding of systems' performance and prediction models, adopting data QA/QC and better knowledge management practices, and ensuring proper staff education/training.

The workshop fell short of specifying measures, targets, and initiatives to achieve the objectives. These aspects are covered in the example framework discussed in the following sections.

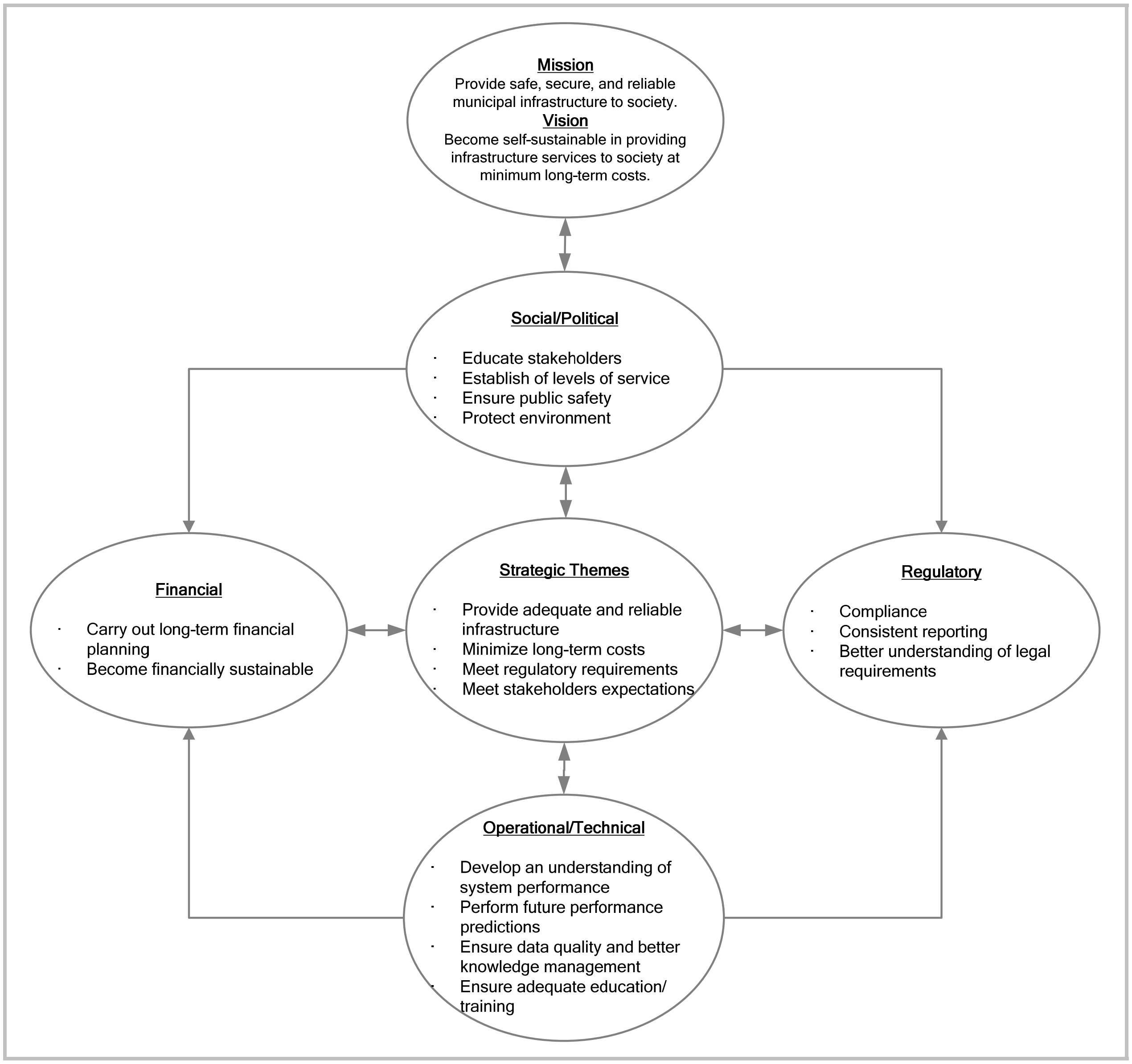

Figure 7.9: Modified Balanced Scorecard Model

7.10 Framework Implementation, Monitoring, and Reporting

A flexible and real-time system for implementing, monitoring, communicating, and managing the framework and scorecard is very important to materialize the benefits of the proposed methodology. For this purpose, data from various business units of the utility are to be aggregated into a data warehouse. Data sources can include departmental information systems from operations, planning and development, finance, infrastructure management, projects and construction, and human resources. In-house or proprietary information technology solutions can be employed to retrieve, store, and disseminate data and information from various data servers. Tools such as Microsoft's SharePoint Server and SQL Server, Oracle's Enterprise Performance Management and Business Intelligence, IBM's Cognos Scorecarding and Business Intelligence, SAP Strategic Enterprise Management, and SAS Strategic Performance Management and Enterprise Intelligence can be used to develop and implement balanced scorecards, manage strategy, and to monitor performance. Other specialty performance and process management systems such as QPR ScoreCard and Corporator Enterprise Performance Management Suite provide useful functionality to manage strategy and operational performance. The software choice and system architecture depends on particular circumstances and requirements of an organization. Specialty tools can be inflexible and difficult to customize for particular utility needs. In-house development, on the other hand, can be slow due to resource constraints. For communicating and reporting performance, *dashboard reporting* is an indispensable tool. Dashboard reports provides visual summary of critical data for efficient and effective decision making.

7.11 Example Framework

The modified balanced scorecard model is used to develop an example management framework for the City of Niagara Falls wastewater collection utility. Due to data constraints and the enormity of the scope of work involved, only operational/technical perspective is described. The following paragraphs discuss the background information, and the implementation of the proposed strategic management system.

7.11.1 The Situation

The City of Niagara Falls wastewater collection network consists of about 400 km of pipelines with a total replacement value of approximately $250 million. Dwindling inspection budgets in mid 80's to mid 90's made the task of network repair and replacement prioritization next to impossible. The historic condition assessment data is virtually useless due to data quality issues resulting from widely varying inspection and reporting practices using Closed Circuit Television cameras. The integrated strategic management framework described in this paper and implemented in the following paragraphs serves as a template and guideline only.

7.11.2 Mission and Vision

The mission of the utility is to provide safe and secure disposal of water from domestic, industrial, commercial, and public usage. The vision is to become self-sustainable to provide reliable service to customers at a minimum cost.

7.11.3 Strategy

Provide adequate and reliable infrastructure at the minimum long-term cost while meeting regulatory requirements and customer expectations.

Thus, the key strategic themes for the City of Niagara Falls wastewater utility include: (1) meet regulatory requirements, (2) provide a reliable and adequate infrastructure, (3) meet customers' expectations, and (4) minimize long-term costs.

7.11.4 The Strategy Map

Figure 7.10 shows the strategy map of objectives for sustainable wastewater infrastructure systems. Four perspectives, shown on the left side of the map, include: operational/technical, social/political, regulatory, and financial. The strategic themes are highly interrelated. The objectives in the operational/technical perspective will dictate/support how the goals in other perspectives (i.e., social/political, regulatory, and financial) will be achieved. For example, in social/political perspective, to ensure public health and safety and to protect environment, current condition – structural, operational, and hydraulic – of wastewater collection network needs to be ascertained. Similarly, in financial perspective, the objective to determine future needs requires that models to understand performance behavior are developed as articulated by objective OT3: Carry out performance modeling/future predictions in operational/technical perspective.

The social/political perspective takes into account various stakeholders – customers and regulatory agencies – that must be satisfied. The objectives of ensuring public health and safety, protecting environment, and meeting customers' expectations under this perspective will ensure the utility's focus on strategic themes. The financial objectives are drawn from the mission and vision of wastewater utility, and are aligned with the strategic themes. To carry out the mission of providing safe and secure disposal of wastewater and fulfill the vision of financial sustainability in the long-run, the utility needs to assess real costs of providing services, devise plans to reduce costs, and determine future financial needs to meet stakeholders' requirements. For example, the current water/wastewater rates, at many utilities, only include operational costs and do not cover the cost of renovation of aging infrastructure. Similarly, many households, which pay flat fee for water and wastewater services, may be brought under metering systems to increase revenue. The objective for regulatory perspective is to ensure that a utility meets all the regulatory requirements and is accountable for its performance.

7.11.5 Modified Balanced Scorecard

The key strategic themes – meet financial and environmental regulatory requirements, provide adequate and reliable infrastructure, meet customers' expectations, and minimize long-term costs – are included in the balanced scorecard. Initially, 14 strategic objectives are identified as shown in Figure 7.10. The objectives are then related to the four identified perspectives of municipal infrastructure management, and measures, targets, and initiatives specified.

Performance Measures, Targets and Strategic Initiatives

The strategy map shown in Figure 7.10 provides an overview of the utility's endeavors. The objectives are translated into measures and targets to keep track of a utility's performance. Strategic initiatives which include plans and projects to achieve objectives are then proposed.

Table 7.2 presents an example of the development of modified BSC for a wastewater collection system with objectives provided in the strategy map. Table 7.2 integrates strategic objectives, and provides measures for the objectives, current and target values for the measures, strategic initiatives, timelines, and resource requirements. As discussed earlier, the presented perspectives, objectives, KPIs, and action plans are provided as a template, and may be revised as deem fit by the utility. The purpose is to provide an example of generic and systematic methodology to link objectives with action plans through KPIs to achieve the strategic mission and vision of the utility.

To facilitate the implementation of the balanced scorecard, an example Data Definition Table (DDT) is provided in Table 7.3 for some of the measures. The DDT defines a measure and provides details such as: measure background – perspective under which it falls, strategic theme, objective, and description; measure characteristics – type, frequency, measurement unit, and polarity; calculation and data – formulae, data source, data quality; and performance information – current/actual/achieved, target, rationale, and initiatives (Niven, 2005).

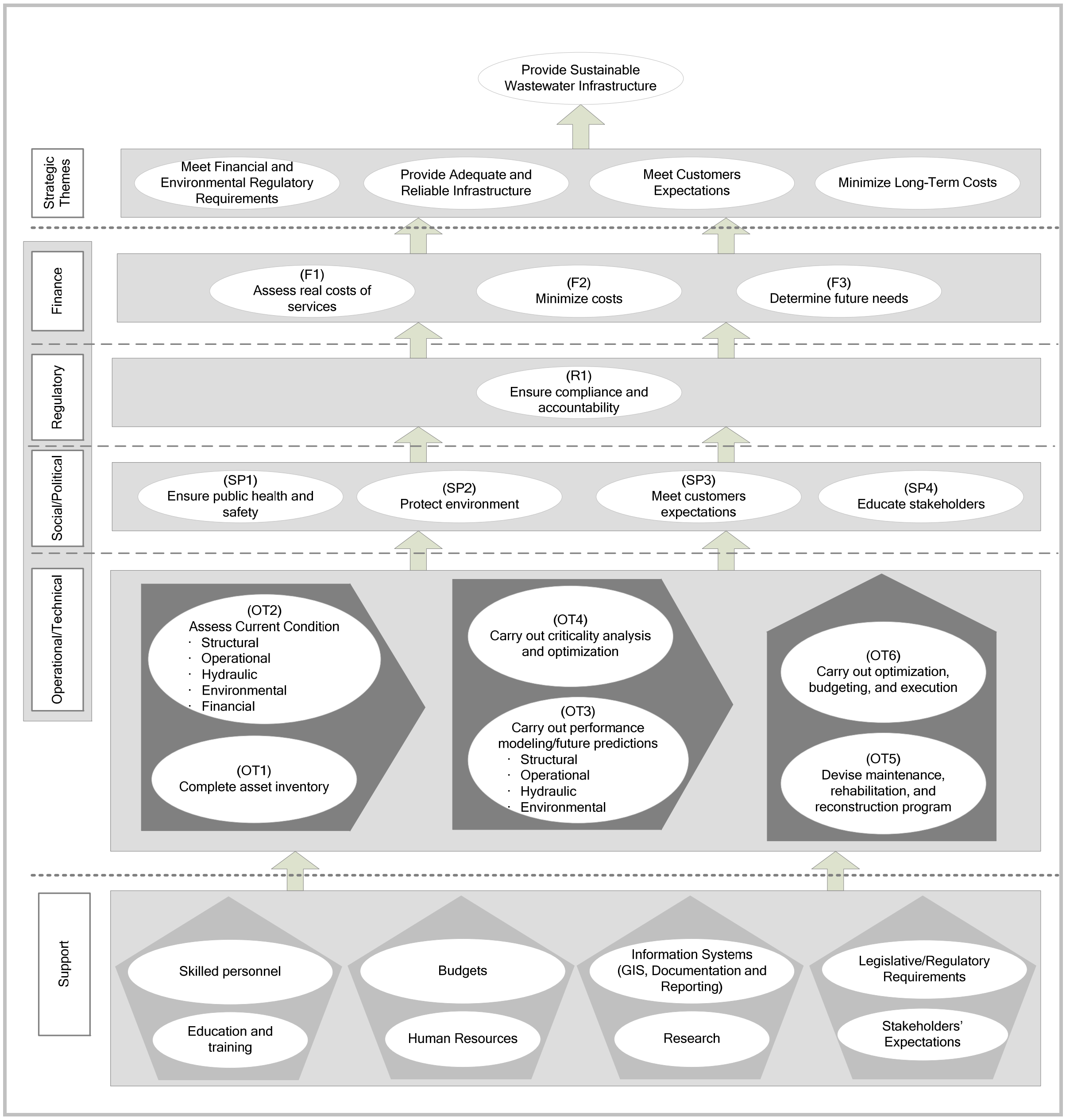

Figure 7.10: Strategy Map for Sustainable Wastewater Infrastructure – an Example

Table 7.2: Modified Balanced Scorecard for Wastewater Collection Systems – An Example

Perspective	Objectives	KPI – Measurements	KPI – Targets /Results	Action Plans	Time Frame	Resource Requirements
Operational /Technical (OT)	**OT1: Complete system inventory**	Percentage of total system cataloged	• *Target*: 5% per month • *Actual*: 4%	• Check construction drawings, perform field surveys, and match data • Update information system	• Two year	• Operating $xxx • Capital $xxx
	OT2: Assess current condition of wastewater collection system • Structural assessment • Operational assessment	Percentage of pipelines inspected	• *Target*: 20% per year • *Actual*: 20%	Initiate a multi-year inspection program	• Five years	• Operating $xxx • Capital $xxx
	• Hydraulic assessment	Percentage of pipelines/locations with capacity/flooding issues	• *Target:* 0% (Eliminate flooding events) • *Actual: x%*	• Monitor flows • Carry out hydraulic modeling • Prepare mitigation projects	• Five year	• Operating $xxx • Capital $xxx
	• Environmental assessment (Ensure no contamination of surface and groundwater and soils due to ex-filtration) Note: for details on Drastic Index, please refer to Aller et al. (1985)	Percentage of area with Drastic Index > 82 e.g., DRASTIC Index Index — Description 37-82 — No Risk 83-128 — Low Risk 129-174 — Moderate Risk 175-226 — High	*Target:* reduce percentage of area with DRASTIC index > 82 to zero *Current:* 10%	• Stage1: Develop surface and groundwater vulnerability maps and devise mitigation plans • Stage 2: Implement plans/projects	• Two years • Within 3 years after stage 1	• Operating $xxx • Capital $xxx
	OT6 Carry out optimization, budgeting, and execution	Percentage of pipelines in condition grade greater than 3	*Target:* reduce the percentage greater than condition grade 3 to zero – 10% per year *Actual:* percent greater than condition grade 3	Develop maintenance, rehabilitation, and reconstruction plans	Ten years	• Operating $xxx • Capital $xxx

Table 7.2 Continued

Perspective	Objectives	KPI – Measurements	KPI – Targets /Results	Action Plans	Time Frame	Resource Requirements
Social/Political (SP)	**SP1: Meet customers' expectations**	Customers satisfaction index (*scale*: 1:best-5:worst)	• *Target*: 1 • *Actual*: 3	• Keep record of customer complaints • Perform quarterly surveys	Perpetual	• Operating $xxx • Capital $xxx
	SP2: Ensure public health and safety	No. of illness cases related to water/wastewater (fatalities, hospitalization etc.)	• *Target*: 0 • *Actual*: 10	Identify system deficiencies and perform emergency repairs	Perpetual	• Operating $xxx • Capital $xxx
	SP2: Ensure public health and safety	No. of illness cases related to water/wastewater (fatalities, hospitalization etc.)	• *Target*: 0 • *Actual*: 10	Identify system deficiencies and perform emergency repairs	Perpetual	• Operating $xxx • Capital $xxx

Table 7.3: Data Definition Table

***Objective*: OT1 Complete system inventory**	*Perspective*: Operational/Technical
Strategy Theme: Provide reliable and adequate infrastructure	
Measure: Percentage of total system cataloged. *Weight*: 5. *Maximum Points*: 50 (rating x weight) *Formula*:	

Range	Rating
91% - 100 %	10
81% - 90 %	9
…	…
0% - 10%	1

Unit Type: Points	*Frequency*: Quarterly	*Polarity*: Higher values are good
Description: This objective provides information regarding the size and scope of infrastructure such as total length, age, material type, depth, soil conditions, live and dead loads, and spatial characteristics.		
Initiatives: 1. Check construction drawings, perform field surveys, and match data 2. Update information system		

***Objective*: OT2 Assess current condition of wastewater collection system**	*Perspective*: Operational/Technical
Strategy Theme: Provide reliable and adequate infrastructure	
Measures:	
Structural condition	Percentage of total system inspected. *Weight*: 5. *Maximum Points*: 50 (rating x weight). *Use rating as in OT1.*
Operational condition	Percentage of total system inspected. *Weight*: 5. *Maximum Points*: 50 (rating x weight). *Use rating as in OT1.*
Hydraulic condition	Percentage of pipelines/locations with capacity/flooding issues. *Weight*: 5. *Maximum Points*: 50 (rating x weight), *Use rating as in OT1.*
Environmental condition	Percentage of area with DRASTIC Index >82, *Weight*: 5. *Maximum Points*: 50 (rating x weight x area)

			Example	
Index	Description	Rating	Area (%)	Points (RatingxAreaxWeight)
37-82	No Risk	10	50	30.0
83-128	Low Risk	7	10	3.5
129-174	Moderate Risk	5	10	2.5
175-226	High	1	20	1.0
			Total	37

Unit Type: Points	*Frequency*: Quarterly	*Polarity*: Higher values are good
Description: This objective is to assess the overall condition of the network.		
Initiatives: 1. Initiate a multiyear inspection program to collect quality condition assessment data. 2. Update information system. 3. Carry out hydraulic and environmental modeling.		

Table 7.3 continued

***Objective*: OT3 Carry out performance modeling**		*Perspective*: Operational/Technical
Strategy Theme: Provide reliable and adequate infrastructure		
Measure: Models exist for each of structural, operational, hydraulic, environment, financial; *Weight*: 2 for each; *Maximum Points*: 80 *Formula*:		
Unit Type: Points	*Frequency*: Perpetual	*Polarity*: Higher values are good
Description: This objective provides estimates for future condition predictions.		
Initiatives: 1. Same as in objectives OT1 and OT2 2. Carry out modeling		

Values	Rating
Yes	10
No	0

***Objective*: OT4 Criticality analysis**		*Perspective*: Operational/Technical
Strategy Theme: Provide reliable and adequate infrastructure		
Measure: Percentage length of pipelines with Hazard Rating Number (HRN) >10. *Weight*: 5. *Maximum Points*: 50 (rating x weight) *Formula*:		
Unit Type: Points	*Frequency*: Perpetual	*Polarity*: Higher values are good
Description: This objective provides an evidence of risk consideration, regulatory compliance, and helps in prioritizing.		
Initiatives: Carry out analysis using, for example, risk assessment or analytical hierarchy process techniques and prioritize assets according to risk		

				Example	
HRN Range	Risk	Rating	Internal Condition Grade	Percentage	Points (RatingxPercentagexWeight)
0-1	Acceptable	10	1	40	20
1-5	Very low	8	2	10	4
5-10	Low	6	3	10	3
10-50	Significant	5	3		
50-100	High	4	4		
100-500	Very high	3	4	20	3
500-1000	Extreme	2	5		
1000+	Unacceptable	1	5	20	1
				Total	31

Table 7.3 continued

***Objective*: OT5 Devise maintenance, rehabilitation and reconstruction program (short and long-term)**		*Perspective*: Operational/Technical
Strategy Theme: Provide reliable and adequate infrastructure		
Measure: Short-term program exists. *Weight*: 5. *Maximum Points*: 50 (rating x weight) Long-term program exists. *Weight*: 5. *Maximum Points*: 50 (rating x weight) *Formula*: Sophistication — Rating High — 10 Medium — 6 Low — 3 No program exists — 0		
Unit Type: Points	*Frequency*: Perpetual	*Polarity*: Higher values are good
Description: This objective measures the forward looking thinking of service providers. This will help in developing multiyear capital investment plan and capital budget.		
Initiatives: 1. Same as in OT1 through OT4. 2. Based on 1, develop multiyear capital improvement and investment plan.		

***Objective*: OT6 Carry out optimization, budgeting, and execution**		*Perspective*: Operational/Technical
Strategy Theme: Provide reliable and adequate infrastructure		
Measure: Optimization program/model exists. *Weight*: 5. *Maximum Points*: 50 (rating x weight) *Formula*: Sophistication — Rating High — 10 Medium — 6 Low — 3 No program exist — 0		
Unit Type: Points	*Frequency*: Perpetual	*Polarity*: Higher values are good
Description: This objective provides an evidence of risk consideration, regulatory compliance, and helps in prioritizing.		
Initiatives: 1. Perform data analysis and modeling		

7.11.6 Implementation, Monitoring, and Reporting

There are many possible system configurations for implementing, monitoring, communicating, and managing the proposed framework. One such architecture is presented in Figure 7.11 where data from various business units of the utility are aggregated into a data warehouse. For the City of Niagara Falls, the example framework has been implemented using QPR ScoreCard software. A sample metrics system is provided for each of the objectives (refer to Table 7.3 and Table 7.4) to monitor the performance and progress within each of the perspectives. For example, from Operational/Technical viewpoint, estimated target score is 450 for a system to be sustainable as shown in Table 7.4.

The City of Niagara Falls, in 2005, embarked on a multi-year wastewater collection system condition assessment program using the Side Scanner and Evaluation Technology. Figure 7.12 shows a sample dashboard report presenting the actual and target progress for objectives OT1 and OT2 since the start of the project. The dial gauges represent the current performance whereas line charts show the trend for the measures actual and target performance. Using the proposed metrics and additional information on other initiatives at the City, the total score in Operational/Technical perspective is estimated to be 232 as shown in Table 7.5. Similarly, scores can be developed for other perspectives.

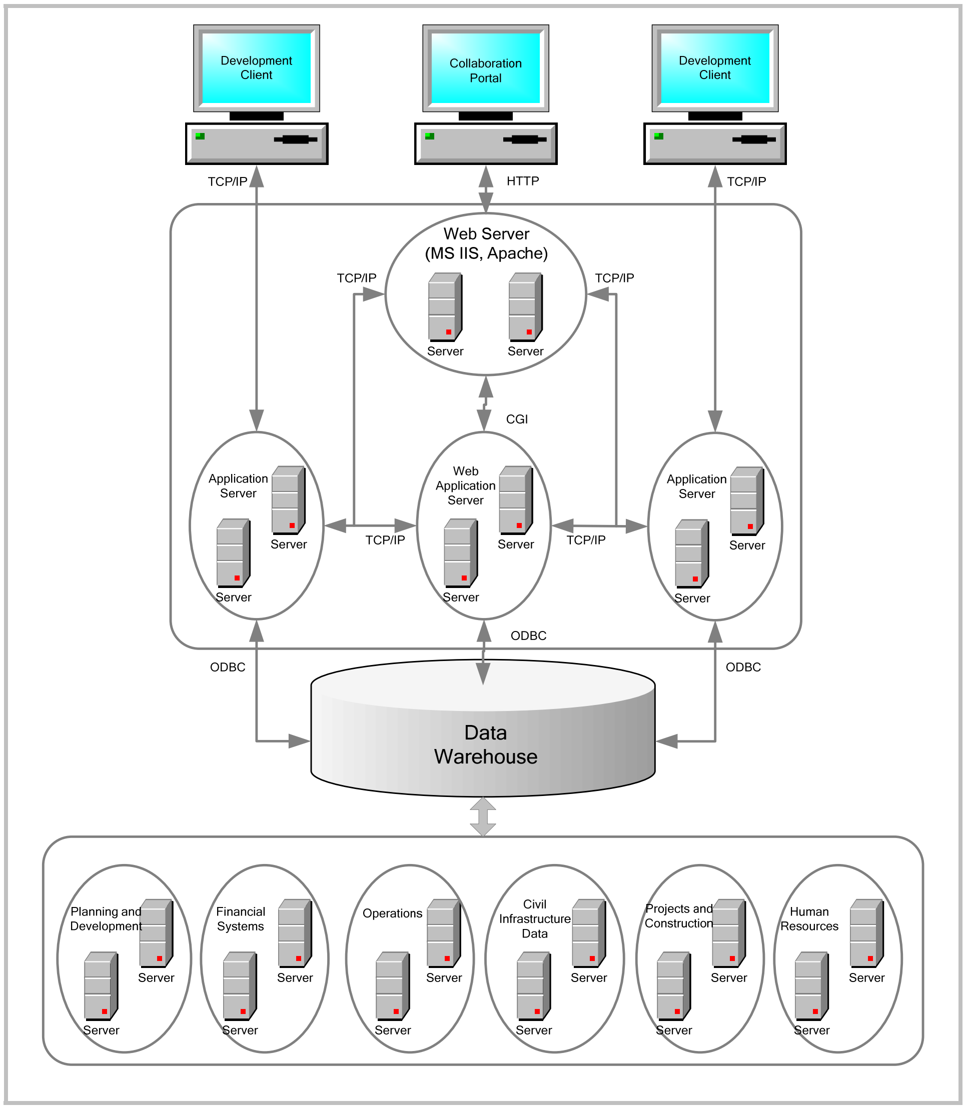

Figure 7.11: System Configuration for Strategic Management Framework

Table 7.4: Operational/Technical Sustainability Metrics

Perspective: Operational/Technical				
Objective	**Measure**	**Maximum Rating**	**Weight**	**Maximum Score**
OT1: Complete System Inventory	Percentage of total system catalogued	10	5	50
OT2: Assess Current Condition	Percentage of total system inspected			
Structural		10	2	50
Operational		10	2	50
Hydraulic		10	2	50
Environmental		10	2	50
Financial		10	2	20
OT3: Performance Modeling	Model exists			
Structural	Yes	10	2	20
Operational	Yes	10	2	20
Hydraulic	Yes	10	2	20
Environmental	Yes	10	2	20
Financial	Yes	10	2	20
OT4: Criticality Analysis	Percentage of pipelines with Hazard Rating No. > 10	10	5	50
OT5: MRR Programs				
Short-Term	Program exists (rating depends on sophistication)*	10	5	50
Long-Term	Program exists (rating depends on sophistication)*	10	5	50
OT6: Optimization, budgeting, execution	Program exists (rating depends on sophistication)*	10	5	50
			Total	**450**

**refer to Table 7.3*

Table 7.5: Operational/Technical Sustainability Score

Perspective: Operational/Technical

Objective	Measure	Current Cumulative Progress	Rating	Weight	Score		
					Actual	**Maximum Possible**	**Alarm**
OT1: Complete System Inventory	Percentage of total system catalogued	78	8	5	40	50	45
OT2: Assess Current Condition	Percentage of total system inspected						
Structural		28	3	2	6	20	18
Operational		28	3	2	6	20	18
Hydraulic		70	7	2	14	20	18
Environmental		50	5	2	10	20	18
Financial		50	5	2	10	20	18
OT3: Performance Modeling	Model exists						
Structural	Yes/No	No	0	2	0	20	18
Operational	Yes/No	No	0	2	0	20	18
Hydraulic	Yes/No	Yes	5	2	10	20	18
Environmental	Yes/No	Yes	5	2	10	20	18
Financial	Yes/No	Yes	5	2	10	20	18
OT4: Criticality Analysis	Percentage in particular hazard range					50	50
	Acceptable	70	10	5	35		
	Low	5	8	5	2		
	Significant/High	10	5	5	3		
	Very High	10	3	5	2		
	Unacceptable	5	1	5	0		
OT5: MRR Programs							
Short-Term	Program exists, Sophistication = Medium		6	5	30	50	50
Long-Term	Program exists, Sophistication = Low		3	5	15	50	50
OT6: Optimization, budgeting, execution	Program exists, Sophistication = Medium		6	5	30	50	50
Total					**232**	**450**	**425**

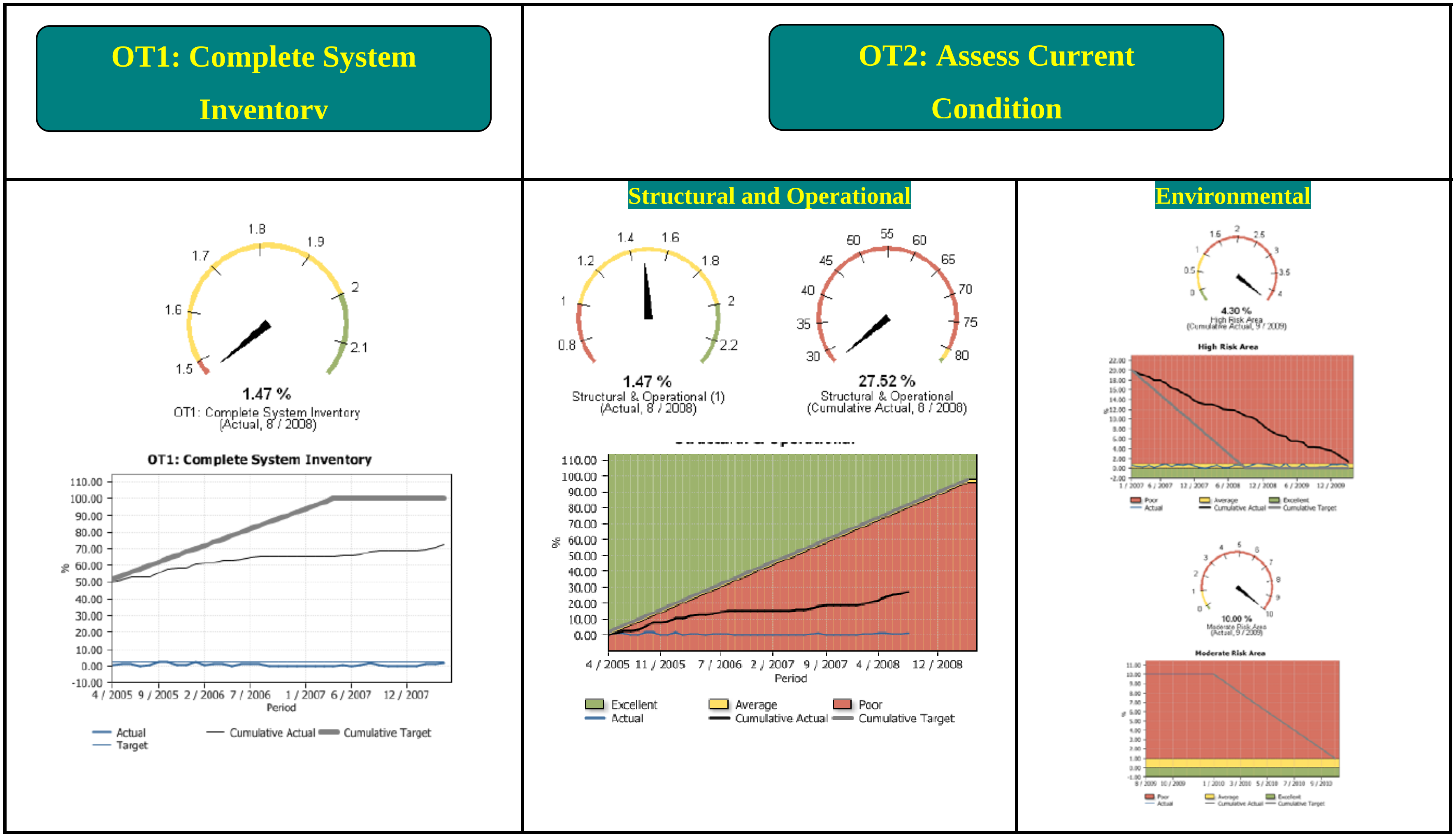

Figure 7.12: Part of the Example Dashboard

7.12 Conclusions

Despite ample published literature on asset management, the implementation of asset management from strategic viewpoint is disappointing. An overwhelming number of utilities either do not have asset management plans or they fail to execute their plans because of gaps between strategy formulation and implementation. Half-hearted and incoherent asset management implementation attempts result in abandonment of initiatives and lead to failures in addressing fundamental infrastructure challenges. Some management tools, such as benchmarking initiatives, are useful for diagnosing problems and identifying utilities that need extra support. However, they are meaningless to assess and compare the real performance of utilities because they evaluate heterogeneous systems and business processes. Benchmarking is also useless in terms of predicting if the services will improve in the future at participating organizations.

To overcome the issues with existing infrastructure management approaches, this paper proposed a new integrated strategic management framework based on modified balanced scorecard model for wastewater collection systems. The proposed framework helps in aligning the asset management strategies with an organization's mission and vision. By using the proposed framework, gaps between strategy formulation and implementation become obvious, and mitigating strategies can be formulated in real time.

The mission, vision, strategy, strategy map, and modified balanced scorecard presented in this paper are meant to provide an example and guide for wastewater utilities. Due to the enormity of the subject, the paper did not discuss all the perspectives in detail. Wastewater

Utilities, being heterogeneous organizations – that is, they have their own independent business processes and organizational structures – may find it necessary to modify the proposed model to suit their own circumstances.

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Chapter 8

Strategic Financial Planning for Wastewater Collection Networks

Part 1: The Framework

8.1 Abstract

The issue of chronic under investment in urban infrastructure maintenance, rehabilitation and replacement (M,R&R) and the resulting infrastructure deficit is well documented in civil infrastructure management literature. This is partly attributed to poor understanding about infrastructure performance behaviour and funding requirements. This paper – first of two papers – presents a framework for strategic financial planning for wastewater collection networks. The framework consisting of four interrelated components – that is, strategic planning, system support, economic analysis and decision support – integrates wastewater collection systems' performance model and economic analysis principles to provide sustainable wastewater collection system at desired service levels. A deterioration model is proposed to predict service levels – in terms of internal condition grades of wastewater collection pipelines – for alternative management scenarios over the planning horizon. The cash flows and decision metrics are then established. A risk-based methodology incorporating Monte Carlo simulations is proposed to take into account the variability in input variables. The rehabilitation costs at different stages of life-cycle of wastewater pipelines, lengths of pipelines in different condition grades and interest (discount) rates are important input variables.

Strategic financial planning has long-term implications on the performance of public works departments – responsible for providing wastewater infrastructure. The proposed framework and methodology will help wastewater collection network administrators to proactively

maintain and manage their wastewater infrastructure and to estimate long-term M,R&R funding requirements.

Keywords: Wastewater pipelines; Economic analysis, Monte Carlo simulations; Deterioration modeling; Ordinal regression; Asset management; Sewer systems.

8.2 Introduction

Civil or urban infrastructure consists of capital intensive physical systems that provide essential services such as transportation (pavements and bridges), utilities (water, wastewater, hydro, gas, telephone), and buildings (offices, health and education facilities). Wastewater collection networks – an important component of municipal civil infrastructure systems – are responsible for safe and secure disposal of water from domestic, industrial, and commercial usage. Aging pipelines, increased structural and operational defects due to continual neglect, and additional demands due to population growth and new developments pose latest challenges in providing these services. Due to financial constraints and competing demands on limited resources it is vital for service providers – that is, public works departments at municipal or regional level along with provincial and federal counterparts – to provide, maintain and manage these systems in an effective, efficient, and sustainable manner.

In Canada, the majority of wastewater collection networks are approaching the end of their estimated service life of 75 to 100 years. Limited understanding about networks' deterioration behaviour and lack of useful estimates about monetary requirements contributed to the chronic under investments in the management and renewal of existing municipal infrastructure systems (Lufkin et al., 2005). Historically, governments at all levels failed to invest adequately into the maintenance, management, and rehabilitation of existing urban infrastructure due to resource constraints (Miller, 2008; Mirza and Haider, 2003; Mirza, 2007). This has resulted in local governments resorting to balance their budgets by deferring maintenance spending (Miller, 2008). Estimates of Canada's municipal infrastructure deficit vary from $44 billion total municipal infrastructure shortfall (TD Economics, 2002) to over $125 billion (Mirza, 2007). The *municipal infrastructure deficit* is an estimate of the total additional investment needed to repair and prevent deterioration in existing, municipally owned infrastructure assets. Mirza (2007) reports that the infrastructure funding gap for existing water and wastewater systems is $31 billion, and to meet new needs an additional $56.6 billion is required. The size and scope of the infrastructure problems facing municipalities and local governments is enormous as the decay of Canada's infrastructure creates severe domino effects – higher cost of maintenance, operation, rehabilitation, and repair; inefficiency and increased vulnerability; and increased threats to public safety and the environment. Mirza (2007) states that "without maintenance or with deferred maintenance, the municipal infrastructure deficit could be close to $2 trillion by 2065, and that with regular maintenance and good scientific management, the escalating infrastructure deterioration and the resulting infrastructure deficit can be controlled within manageable levels."

Budgetary shortfalls have placed public works departments under increased pressure to be financially self-sustainable while at the same time meeting increased public fiscal scrutiny and regulatory requirements. For example, in Ontario, Canada, Regulation 453/07 under Safe Drinking Water Act, 2002, requires that current and future financial plans for water systems sustainability must be prepared and made public to obtain operating permits. The Canadian Institute of Chartered Accountants Public Sector Accounting Board (PSAB) issued statement PS3150 in 2006 which requires all Canadian municipalities and utilities, starting in January 2009, to report their tangible capital assets along with their depreciation on financial statements (OMBI, 2007). In the United States, the Governmental Accounting Standards Board (GASB) Statement 34, and in Australia, the Australian Accounting Research Foundation Standard 27 specifies similar accounting practices (see FHWA, 2000; Howard, 2001).

Strategic financial plans need to be developed to implement asset management strategy, ascertain real costs of providing desired level of services, and achieve strategic objective of providing sustainable wastewater collection networks. Strategic financial planning – an integration of economic analysis principles with strategic planning process – can help in urban infrastructure strategic management. It involves decision-making about significant investments in long-lived assets, and has long-term impacts and implications on an organization’s performance. To develop useful management plans, an understanding of system performance behaviour – in terms of structural deterioration model(s) – of wastewater collection systems is critical. This will enable wastewater service providers to assess the timing and extent of capital expenditures, and hence develop a long-term fiscal policy to pro-actively maintain and manage these systems.

This paper discusses a framework for strategic financial and rehabilitation/reconstruction planning for wastewater collection systems based on service orientation principles. The framework integrates strategic planning process with the performance and financial simulation models to develop and analyze a range of possible strategies for effective management of wastewater collection networks. Fundamental definitions/formulas for economic analysis are provided, and Monte Carlo simulations are used to demonstrate the impact of variability of input variables on decision metric(s). Part 2 of the series presents a case study showing the application of performance model and financial simulation for strategic financial and rehabilitation/reconstruction planning of wastewater collection pipelines.

8.3 Overview of Economic Analysis for Wastewater Infrastructure Management

The literature on civil infrastructure life-cycle economic analysis and financial planning can be broadly classified into two categories: (1) *optimized selection* of maintenance, rehabilitation, and replacement (M,R&R) techniques with or without financial constraints; and (2) *strategic financial planning* – that is, the identification of short- and long-term funding needs and development of capital budgets. The work in strategic financial planning – that is, the development of long-term financial plans for sustainable wastewater infrastructure at network-level – is scarce. According to Lufkin et al. (2005), estimates of public infrastructure restoration and modernization costs, at many organizations, are "based on ad hoc approximations or historical trends," and are not credible.

The most commonly used methods for infrastructure investment analysis include *Benefit/Cost Ratio*, *Internal Rate of Return*, *Equivalent Uniform Annual Costs*, *Cost-Effectiveness*, and *Present Worth* (Hudson et al., 1997). Haas et al. (2006) noted that Present Worth method has been used exclusively in pavement management field. Markov Decision Process (MDP) or Probabilistic Dynamic Programming (PDP) is another commonly used technique for maintenance, management, and rehabilitation planning for transportation (pavements and bridges) and water/wastewater infrastructure. According to Hillier and

Lieberman (1980), “MDP is a general model for PDP where stages [that is, condition grades in case of civil infrastructure] continue to recur indefinitely.” In MDP applications, deterioration is modeled as a finite-state Markov chain process with known or assumed state transition probabilities. Alternative maintenance and rehabilitation policies – that is, decisions and actions – and costs are specified for different condition grades of infrastructure over the planning horizon. An optimal decision is then selected using linear programming or policy improvement algorithms for each condition grade.

Considerable literature exists on the application of above methods for transportation infrastructure management. The U.S. Department of Transportation, Federal Highway Administration (FHWA) emphasizes the use of life-cycle costing analysis to quantify the costs for alternative investments for new and existing transportation infrastructure (FHWA, 2002). NCHRP (2003) published a detailed report on life-cycle cost analysis for bridges. The NCHRP report describes a procedure for the selection of cost-effective techniques for repair and rehabilitation of bridges for short- and long-term planning. Haas (2007) highlighted the need for new and better tools for Life-Cycle Cost Analysis (LCCA), and noted that the selection of the best LCCA method for civil infrastructure depends on the application, understanding, and consistency. Further details on published studies are provided in the second paper of the two paper series.

8.4 Proposed Strategic Financial Planning Framework

Strategic planning is not new, and there is a considerable body of strategic planning literature applicable to private, government and non-profit sectors. However, it is noted that strategic planning theories and principles found limited application in wastewater infrastructure management field. The proposed strategic financial planning framework comprises of four interrelated components – that is, strategic planning, system support, economic analysis and decision support – having 12 elements as illustrated in Figure 8.1 and detailed in Table 8.1. The following sections discuss the proposed framework and provide basic definitions and processes involved in strategic financial planning.

8.4.1 Strategic Planning

The strategic planning is a cyclic process that involves envisioning and describing a future, assessing present situation, defining initiatives and key success factors, and identifying desired programs and alternatives (Bryson, 2004). Figure 8.1 shows the four basic elements of strategic planning component, that include: (1) vision, mission and goals; (2) situation analysis; (3) decision metrics; and (4) desired scenarios and programs/initiatives.

Vision, Mission, and Goals

Vision defines an organization's desired future – that is, what it wants to ultimately achieve; whereas, mission describes business(s) that an organization intends to pursue (Dess et al., 2006). According to Dess et al. (2006) and Thompson (1998), sometimes vision and mission are used interchangeably; however, vision is the foundation of mission. Developing vision and mission statements, as well as, creation of goals and specific objectives are the first step in the strategic planning process. Many municipalities have developed vision and mission statements and identified programs/actions, but they usually fall short on implementing their strategy due to lack of knowledge, incomplete information, and insufficient resources.

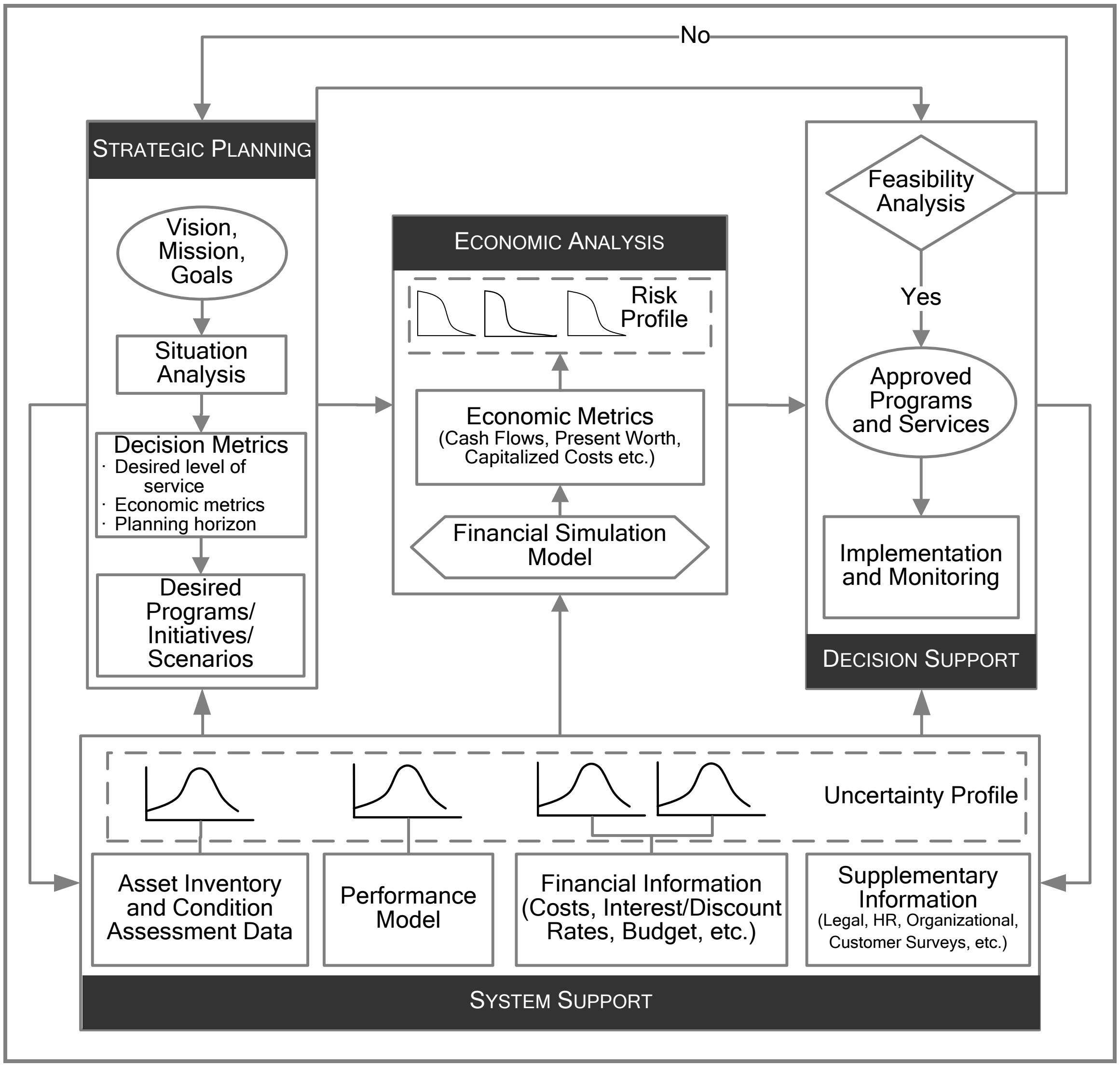

Figure 8.1: Strategic Financial Planning Framework for Wastewater Collection Networks

Table 8.1: Strategic Financial Planning Framework for Wastewater Collection Networks

STRATEGIC PLANNING
Element 1: Vision, Mission, and Goals
• Intended direction
• Central purpose of organization
• Ultimate objectives to be achieved
Element 2: Situation Analysis
• Analysis of operating environment including regulatory and legal requirements
• Organizational strengths and weaknesses, and major issues
• Current issues and future needs
Element 3: Decision Metrics
• Desired levels of service
• Economic metrics
Element 4: Desired Programs/Initiatives/Scenarios
• Specific programs or steps deemed appropriate
SYSTEM SUPPORT
Element 4: Asset Inventory and Condition Assessment Data
• Detailed account of assets and their condition using consistent and standardized protocols
Element 5: Performance Model
• Understanding system deterioration behaviour
Element 6: Financial Information
• Cost of doing business
• Projects
Element 7: Supplementary Information
• Stakeholders input, customers' surveys
• Legislative and regulatory requirements
• Organizational information
ECONOMIC ANALYSIS
Element 8: Financial Simulation Model
• Monte Carlo Simulations
Element 9: Economic Metrics
• Cash flows for alternative management scenarios and levels of service
• Present worth, Capitalized cost
DECISION SUPPORT
Element 10: Feasibility Analysis
• Operational, technical, legal, and socio-economical viability of initiatives
Element 11: Approved Programs and Services
• Action plans and specific tasks to be completed
Element 12: Implementation and Monitoring
• Projects/plan execution and performance monitoring

Situation Analysis

The purpose of situation analysis is to assess current operating environment, identify present and future trends, perform needs analysis and discover gaps. Part of situation analysis involves carrying out a SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis. As shown in Figure 8.1, System Support component of the proposed framework provides necessary data and information for performing this task.

Decision Metrics

Decision metrics are the measures against which organizational and system performance or projects' outcomes are evaluated (Greenberg, 2003). To assess alternatives, multiple decision metrics, such as desired and/or agreed level of service and economic metrics (i.e., present value, capitalized costs) can be applied. Additional metrics, e.g., environmental indices, can also be included.

Desired and/or Agreed Level of Service

Level of service (LOS) can be defined as operational standards desired and/or need to be maintained by a wastewater collection service provider in consultation with various stakeholders. The stakeholders may include customers and federal, provincial and municipal governments and regulators. Although, there have been attempts to devise performance indicators for wastewater collection systems (see for e.g., Ashley and Hopkinson, 2002; Burke, 2005; Cox et al., 2003; Crotty, 2003; Lafferty and Lauer, 2005), there are no known, established levels of service for wastewater collection systems. For illustration, WRc's

(Water Research Centre, UK) structural internal condition grades are considered as the levels of service in this framework; although, additional service measures may be devised.

WRc specified four performance perspectives, namely, hydraulic, environmental, structural and operational. Majority of the hydraulic and environmental issues, such as overflows, surcharging and infiltration/exfiltration, result from structural and operational defects (e.g., open joints, cracks, fractures, holes, broken pipe segments, grease, debris, roots, blockages etc.,) provided there is adequate flow capacity in system. Therefore, considering structural internal condition grades as a metric for service level is plausible. Table 8.2 shows the WRc's structural internal condition grades and their implications.

Economic Metrics

A wide variety of financial performance metrics are available depending upon an organization's objectives. According to Greenberg (2003), economic metrics can be classified into cost- and price-based decision measures, and multiple metrics are employed in government and private sectors. Greenberg (2003) further argued that cost-based metrics (e.g., net present value) seek cost minimization and are most suitable for governmental service providers, whereas price-based metrics (e.g., return on investment) seek profit maximization and are generally employed by private sector. For illustration, present worth is selected as an economic metrics. Present worth and additional economic metrics are further detailed in Section 8.4.3.

Planning Horizon (Life-Cycle Analysis Period) and Co-termination

Planning horizon – finite or infinite – is the time under study. Different project alternatives or scenarios can have different life-cycles. Therefore, for valid comparisons of competing alternatives, it is important to have same planning horizon (Hudson et al., 1997; Lang and Merino, 1993). *Co-termination* is used to provide common planning horizon for competing alternatives. Lang and Merino (1993) discussed: (1) The Lowest-Common-Multiple; and (2) Early-Sale, co-termination methods in detail. Another option to co-terminate different project alternatives is to consider an infinite planning horizon. According to Lang and Merino (1993), the assumption of infinite life for long-lived assets simplifies the analyses and results in negligible error in computations.

Wastewater pipelines are long-lived assets, and therefore, capital investment plans, budgeting decisions and cash flows may spread over many years. For wastewater pipelines, the life-cycle can be in the range of 50 to over 100 years (Hudson et al., 1997; NAMS, 2002; Younis and Knight, 2009).

Desired Programs/Initiatives/Scenarios

This involves articulating specific programs and alternate scenarios for further analyses. For example, an organization may contemplate between options, such as replacing all grade 5 (i.e., collapsed or nearly collapsed) sewers versus replacing grade 5 and renovating grade 4 (i.e., pipes having major defects e.g., multiple fractures, holes etc.) pipes. After economic and feasibility analyses, some programs or initiatives may turn out to be unfeasible and need revision. For example, it is possible that logistics for a desired imitative may not be practical due to financial limitations, or technical and socio-political reasons.

8.4.2 System Support

The system support provides necessary data and information – that include, inventory and condition, performance, environmental, statutes and regulatory law, stakeholders' input, and financial – for carrying out situation/gap analysis, developing an understanding of systems' performance, and performing out life-cycle analysis.

Asset Inventory and Condition Assessment Data

Remotely controlled Closed Circuit Television (CCTV) and more recently Side Scanning Evaluation Technology (SSET) cameras also known as Sewer Scanner and Evaluation Technology (SSET^{TM}) are used for visual inspections of interior of wastewater pipelines. Pipeline inspections are completed by an operator remotely moving the camera down the pipeline and coding all observed defects using a defect condition coding system. In North America, two wastewater pipeline defect condition Classification systems are predominately used: (1) Manual of Sewer Condition Classification (MSCC) 3rd edition defect coding system developed by Water Research Center (WRc) in the United Kingdom; and (2) Pipeline Assessment and Certification Program (PACP) developed by National Association of Sewer Service Companies (NASSCO) and WRc.

The Manual of Sewer Condition Classification, first published in 1980, became the national standard in the UK and many other parts of the world. In 1994 and 2004, the 3rd and 4th

editions of MSCC were published by WRc, respectively. In 1994, the North American Association of Pipeline Inspectors (NAAPI) adopted WRc's MSCC 3rd edition and developed a certification program for CCTV operators and reviewers. In 2002, NASSCO published PACP to meet the needs of the United States. The Sewerage Rehabilitation Manual (SRM), also published by WRc, describes a wastewater pipelines renovation decision-making process that is adopted in the United Kingdom and Canada. The first edition of the SRM was published in 1986 and the current fourth edition was published in 2001.

The SRM determines the structural and operational performance of wastewater pipelines by assigning scores to MSCC defects based on their type and severity. The structural defect scores are transformed – based on pipeline's peak defect score – to structural Internal Condition Grade (ICG) of 1 to 5, with 1 being the best or acceptable and 5 being the worst or near collapsed state. Table 8.2 provides a summary of implications for each internal condition grade. The continued use of the SRM methodology, in United Kingdom and Canada since 1994, validates the methodology as an acceptable and good approach for determining pipeline current condition states. The general principles of the SRM also form the basis for the European Standard EN752-5 – Drain and Sewer Systems Outside Buildings: Part 5 Rehabilitation. This further validates the SRM approach and provides the rationale for considering ICG as potential service levels in addition to other criteria.

Table 8.2: Internal Condition Grades (WRc, 2001)

Grade	Implication
5	Collapsed or collapse imminent
4	Collapse likely in foreseeable future
3	Collapse unlikely in near future but further deterioration likely
2	Minimal collapse likelihood in short term but potential for further deterioration
1	Accepted structural condition

Performance Model

Performance models reveal degradation behaviour of physical infrastructure systems and provide estimates of their service lives. According to Hudson, Hass et al. (1997), “a performance model relates a selected performance indicator to a set of causal variables such as age, load, load repetitions, usage history, material properties, environmental factors, and M,R&R (maintenance, rehabilitation and reconstruction) history.”

Performance models are one of the most important components of infrastructure strategic management and life-cycle analyses. For wastewater pipelines, the performance behaviour can be affected by factors, such as, *age, material, design and construction practices, and operating environments* (Ariaratnam et al., 2001; Baik et al., 2006; Hudson et al., 1997; Younis and Knight, 1999).

Depending upon modeling objectives, study design and data, various statistical techniques can be applied to develop useful performance models (see for example, Chapters 5, 6 and 7).

A performance model for wastewater pipelines is detailed in Younis and Knight (2009). Below is a summary of the proposed model that predicts *the probability of a wastewater pipeline being in one of the five internal condition grades as opposed to the others* depending upon covariates such as pipe *age* and *material*. This is accomplished by using an ordinal regression model based on cumulative logits using *Generalized Linear Model (GLM)* formulation.

A regression model for ordinal response, Y, based on cumulative probabilities may be specified as (Agresti, 2002):

$$P\left(Y \leq j \mid \mathrm{x}\right) = \pi\left(\mathrm{x}\right) = F\left(\mu_j - \beta_j' \mathrm{x}\right) \tag{8.1}$$

where, the index $j = 1, 2, ..., J$ represents J ordered responses, $F\left(.\right)$ represents the standard cumulative distribution function (cdf) – *logistic* in this case, and μ_j represent the $\left(J-1\right)$ thresholds corresponding to the ordered categories of response variable. This is the Generalized Linear Model (GLM) formulation when F(.) is the inverse link function. The log-odds transformation known as *logit* is the inverse function for the standard logistic cdf. Equation 8.1 can be written as:

$$F^{-1}\left[\pi\left(\mathrm{x}\right)\right] = \mathrm{logit}\left[P\left(Y \leq j|\mathrm{x}\right)\right] = \mu_j - \beta_j' \mathrm{x} \tag{8.2}$$

Using Equation 8.2, the probability of being in a certain category $j = 1, 2, ..., J$ is given by the difference between cumulative probabilities, that is:

$$P\left(Y=j \mid \mathrm{x}\right)=P\left(Y \leq j \mid \mathrm{x}\right)-P\left(Y \leq j-1 \mid \mathrm{x}\right) \tag{8.3}$$

The likelihood function is given as:

$$L=\prod_{i=1}^{n}\prod_{j=1}^{J}P\left(Y=j \mid \mathrm{x}\right)^{c_{ij}} \tag{8.4}$$

where $c_{ij}=1$ if $Y=j$, and 0 otherwise.

Thus, for each J, Equation 8.4 shows the product of all observations for which $Y=j$. The log-likelihood equation is then given as:

$$\log L=\sum_{i=1}^{n}\sum_{j=1}^{n}c_{ij}\log\left[F\left(\mu_j-\beta_j\mathrm{x}\right)-F\left(\mu_{j-1}-\beta_j\mathrm{x}\right)\right] \tag{8.5}$$

Newton-Raphson or Fisher Scoring algorithms can be employed to compute maximum likelihood estimates for model parameters β_j and μ_j.

Financial Information

Financial information pertains to cost/benefit data, information about interest/discount rates and inflation and cash flows.

Cost and Benefit Data

For life-cycle economic evaluation of desired programs, historic construction cost data or monthly and annually published data from sources such as Engineering News Record and R.S Means Company, Inc., may be used.

Interest/Discount Rate and Inflation

According to Hudson et al. (1997), many agencies look at a range of discount rates and use *inflation adjusted discount rate* – that is, the difference between borrowing or investing interest rate minus inflation – for comparing infrastructure investment alternatives. Hudson et al. (1997) argued that "inflation should only be used for setting real discount rates" in economic analysis for infrastructure management systems, and that considering inflation as an additional factor does not result in better selection of alternatives. The study by Wirahadikusumah and Abraham (2003) found that optimal maintenance and rehabilitation alternatives were not affected by inflation and interest rates.

Cash Flows – Timing and Compounding

End-of-year cash flows assumption is commonly used in economic analysis. Lang and Merino (1993) state that the error due to this assumption is negligible and does not distort the results. Another common practice in economic analysis is to use discrete cash flows with discrete compounding for preliminary studies (Lang and Merino, 1993). However, discrete cash flows with continuous compounding or continuous cash flows with continuous compounding are also possible.

End-of-year discrete cash flows and discrete compounding are proposed for financial analysis in this framework. According to Lang and Merino (1993), cash flows far into the future do not significantly contribute to present worth, and therefore, the discrete cash flows assumption is plausible for restoration/rehabilitation costs.

Supplementary Information

Scope of Work

The pipe lengths to be rehabilitated during a specified period (e.g., per year or per five year etc.) over the life-cycle analysis horizon need to be estimated using the deterioration model. However, actual rehabilitated length during each period may vary, and may be assumed to follow a particular distribution (e.g., normal) with upper and lower bounds set for alternative management scenarios, for example, as: (1) *predicted length in internal condition grades 4 and 5* $\pm 20\%$ for management scenario 1; and (2) *predicted length in internal condition grades 3, 4, and 5* $\pm 20\%$ for management scenario 2, and so on.

Stakeholders' Input and Education

One of the most critical and important elements to provide sustainable wastewater collection services involves the determination levels of service and associated costs. The stakeholders need to know and agree upon cost of service and related service levels. This may also require revamping of accounting systems to estimate actual costs of providing wastewater collection services. Bryson (2004) discussed more than a dozen techniques and models for stakeholders' identification, consultation and analysis, which may be useful to obtain stakeholders' input, resolving conflicts and consensus building.

8.4.3 Economic Analysis

Economic analysis supports decision-making related to allocation of resources for infrastructure management initiatives. The economic analysis techniques may be classified as (Crundwell, 2008; Dayananda et al., 2002; Outreville, 1998): (1) discounted cash flow (e.g., net present value, internal rate of return); and (2) non-discounted cash flows (e.g., payback period, accounting rate of return). According to Crundwell (2008); Dayananda et al. (2002);

and Outreville (1998), discounted cash flow analysis is preferred to non-discounted cash flow analysis as the later generally ignores the time value of money. The *time value of money* – one of the most fundamental principles of finance – dictates that cash flows occurring in different time periods should be converted to a common denominator to compare and rank capital investment decisions (Lang and Merino, 1993; Hudson et al.,1997). The *three worths* (Lang and Merino, 1993) used to translate cash flows to a common denominator include: (1) Present Worth (PW), or Present Value (PV), or Net Present Value (NPV); (2) Future Worth (FW), Future Value (FV), or Net Future Value (NFV); and (3) Annual Worth (AW), or Annual Cost (AC) in case of cash outflows, or Equivalent Annual Uniform Cost (EUAC). Any one of the three worths can be converted to the other two using an appropriate discount rate, such as government bond yields or insured banks' term deposit rates (Dayananda et al., 2002). Using factors provided in Table 8.3, the three worths are defined below (Lang and Merino, 1993):

Present worth (PW) is the net equivalent amount of net cash flows (difference between cash disbursements and receipts) at present for a selected interest rate, and is defined as:

$$PW(i) = (P/F, i, t)\, C_t$$
$$PW(i) = \sum_{t=1}^{n} (1+i)^{-t}\, C_t \qquad (8.6)$$

where $PW(i)$ is present worth at interest rate i for an investment for a life of n years, and C_t is the net cash flow at time t.

Future worth (FW) is the net cash flow at some common time point in the future, and is defined as:

$$FW(i) = (F/P, i, n-t)C_t$$

$$FW(i) = \sum_{t=1}^{n} (1+i)^{n-t} C_t \text{, or} \tag{8.7}$$

$$FW(i) = PW(i)(F/P, i, n) = PW(i)(1+i)^n$$

where $FW(i)$ is the future worth at interest rate i, C_t is the cash flow at end of period t.

Annual worth (AW) is the annual equivalent of net cash flow, and is defined as:

$$AW(i) = PW(i)(A/P, i, n) = PW(i)\frac{i(1+i)^n}{(1+i)^n - 1} \tag{8.8}$$

where $PW(i)$ is the present worth at interest rate i.

Table 8.3: Factors for Rate-of-Return Formulas – Discrete Cash Flows and Discrete Compounding (adapted from Lang and Merino (1993))

Factor Name	Factor Symbol	Functional Format	Factor Formula
Present Worth Factors for Discounting			
Single Payment	P/F	$(P/F,\ i,\ n)$	$\frac{1}{(1+i)^n}$
Uniform Series (Annuity)	P/A	$(P/A,\ i,\ n)$	$\frac{(1+i)^n - 1}{i(1+i)^n}$
Future Worth Factors for Compounding			
Single Payment	F/P	$(F/P,\ i,\ n)$	$(1+i)^n$
Uniform Series (Annuity)	F/A	$(F/A,\ i,\ n)$	$\frac{(1+i)^n - 1}{i}$
Annuity Factors for Uniform Series			
Capital Recovery	A/P	$(A/P,\ i,\ n)$	$\frac{i(1+i)^n}{(1+i)^n - 1}$
Sinking Fund	A/F	$(A/F,\ i,\ n)$	$\frac{i}{(1+i)^n - 1}$

Financial Simulation Modeling

The variability in input variables (i.e., cash flows, interest rates, and forecasted scope of renovation/replacement work) results in uncertainty in decision metrics (i.e., present worth or capitalized cost). Emblemsvag (2003) mentioned, "in the literature, many talk about handling uncertainty, but very few actually do it, and in the industry even fewer do it." Emblemsvag (2003) discussed three methodologies to deal with uncertainty that include: (1) probability estimates; (2) Bayesian statistics; and (3) theory of fuzzy numbers and fuzzy inference. Monte Carlo Simulation (MCS) can be employed to account for uncertainty of input variables. Emblemsvag (2003) argued that Monte Carlo simulations provide "the most versatile handling of uncertainty" and outperforms other numerical methods in solving management problems.

MCS involves generating a series of values for model variables within the user-specified parameters using a computer program (e.g., @Risk: http://www.palisade.com/risk/ or Oracle Crystal Ball). The model is evaluated at each of the possible values resulting in a series of output values. Figure 8.2 shows the steps involved in MCS, namely: (1) identifying key input variables and parameters, such as costs, cash flows, discount rates, and pipe lengths to be rehabilitated; (2) specifying probability distributions for input variables to incorporate uncertainty; (3) generating pseudo random numbers of input variables from assumed distributions; and (4) calculating decision metric(s). This procedure is repeated many times – hundreds or thousands – to produce the distribution of output variable. Risk related to uncertainty is estimated as the probability that decision metrics will exceed certain threshold values. According to Chouddry (2006), parameters are specified such that simulated input variable values approximate to normal distribution. However, other distributions such as triangular, uniform, and truncated normal are also used in MCS (Emblemsvag, 2003; Lang and Merino, 1993).

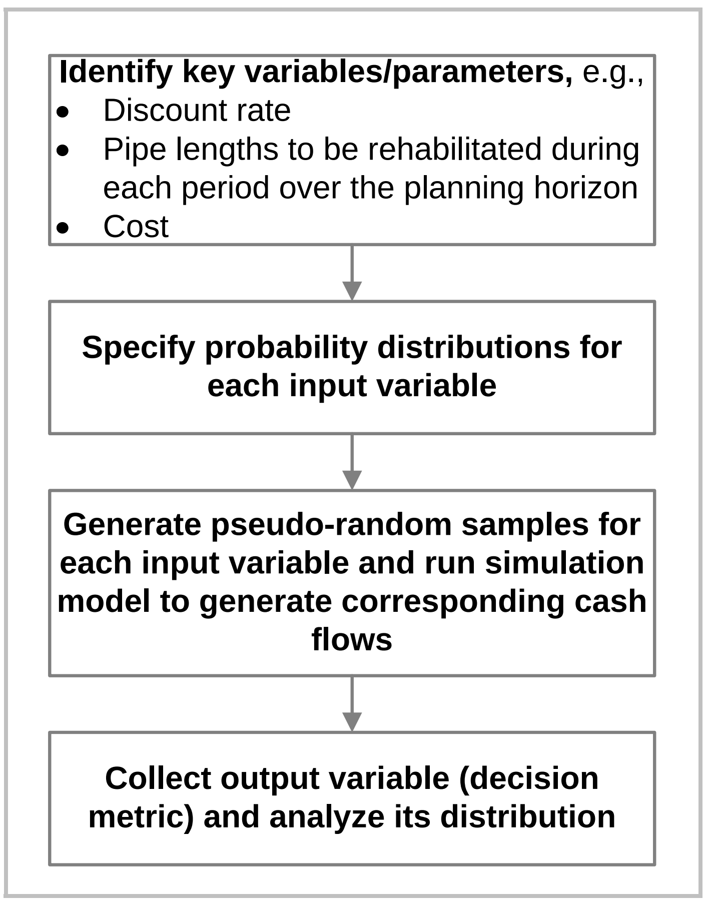

Figure 8.2: Financial Simulation Steps

8.4.4 Decision Support

It is highly unlikely that all the proposed programs and initiatives meet strategic objectives, socio-political constraints, and technical and resource requirements. Decision support component involves carrying out feasibility analysis for various alternatives, prioritizing candidate program(s) and selecting the one(s) that best meet strategic objectives.

Feasibility Analysis, Approved Programs and Services

The proposed alternatives are evaluated against strategic objectives over the planning horizon. Feasible programs proceed to the execution stage, whereas unfeasible initiatives are dropped or revised. For some alternatives, suitable materials, personnel and equipment may not be available or proposed programs may not be feasible in terms of scope and extent of work. For others, appropriate finances may not be readily available and, therefore, they need to be revised or delayed to an indefinite time. Thus, feasibility evaluation concerns with technical, environmental, socio-economic, and legal perspectives. In some instances, unfeasible initiatives can force the redefinition of an organization's strategic objectives.

The economic feasibility may be determined by plotting risk profiles for selected economic metric(s) and carrying out risk comparison of alternatives (Greenberg, 2003). Figure 8.3(a) shows hypothetical risk profiles. It may be noted that alternatives A and B, in Figure 8.3, has same expected costs (at probability=0.5), however, the flatter slope for alternative A shows that it is riskier (more variability) than alternative B. In Figure 8.3(b), hypothetical risk comparison of alternatives 1, 2, 3 and 4 is shown. Alternatives 1 and 2 assume similar risk, but alternative 2 is costly. Alternative 4 offers least cost and risk option. Majority of the existing literature on economic life-cycle analysis for physical infrastructure systems takes into account only the expected values of decision metric(s), and the risk in terms of variability of decision metric(s) is ignored. It is to be noted that *risk* as defined here refers to the variance (Kühn, 2006) - the square root of which is called standard deviation – of the decision metric, and the idea of *risk comparison* is borrowed from the theory of investment finance – the modern portfolio theory and efficient frontier (i.e., mean-variance efficient combinations) – where a plot of expected return versus risk of possible investment opportunities is created for investors to select the desired risk-return combination (see Gallati, 2003; Strong, 2000).

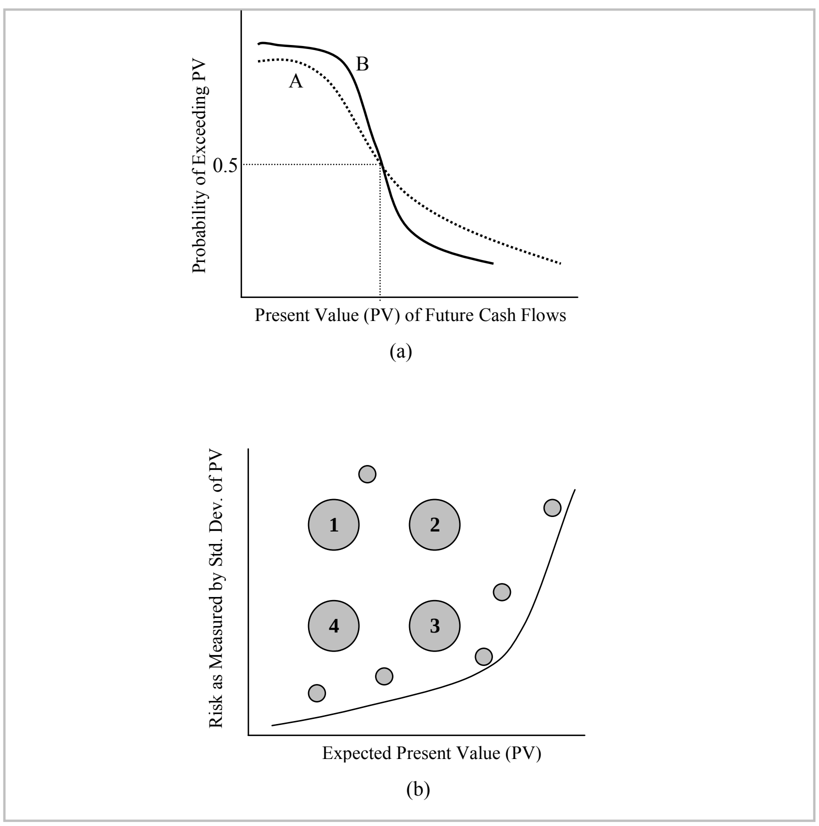

Figure 8.3: Economic Feasibility Analysis (adapted from Greenberg, 2003)

Implementation and Monitoring

This stage involves developing an implementation plan, implementing the plan, and measuring and communicating results. Implementation plan contains details about specific actions required under selected alternative(s), timeline, and a resource plan that includes information about roles and responsibilities, funding and material etc. The results should be evaluated against decision measures, and strategies may be amended based on feedback analysis.

8.5 Discussion and Conclusions

Strategic financial planning – not prevalent in the provision of wastewater collection infrastructure – involves decisions about alternative investment strategies in long-lived assets. Most of the economic decisions relating to infrastructure management involve uncertainty and risk due to unpredictable events, decisions and actions, as well as, variability in cost and interest/discount rates. The risk-based economic analysis methodologies found in literature – mostly in transportation infrastructure management – do not explicitly and quantitatively characterize the uncertainty of output variable or decision metric. This may result in the selection of a *low-cost, high-risk* management decision.

This paper presented a financial planning framework that integrates performance modeling and service levels with economic principles for risk-based strategic financial planning and decision-making for sustainable wastewater collection infrastructure. The service level is described in terms of structural internal condition grades of wastewater pipelines. The proposed deterioration model provides estimates of probabilities of being in a particular condition grade depending upon *age* and *material* for wastewater pipelines. The deterioration model is used to predict the condition of pipelines and corresponding cash flows under a variety of management scenarios. Suitable probability distributions are specified for input variables and random samples (pseudo random) are generated for each of the input variable. The output from Monte Carlo simulation is represented as risk profiles (e.g., a cumulative distribution function plots) and summarized in terms of mean and variance.

The second paper of the two paper series uses the proposed framework to addresses the following questions at the network level:

1. How various management strategies/scenarios will affect network condition over the life-cycle analysis period?

2. What are the financial implications of different intervention plans – that is, the amount of yearly renovation/replacement work – over the life-cycle analysis period?

3. What funding level is required to get the network to a sustainable level?; and

4. What happens if economic conditions – that is, interest rate – change over the life-cycle analysis period?

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Chapter 9

Strategic Financial Planning for Wastewater Collection Networks

Part 2: Application and Results

9.1 Abstract

This paper, second in the two part series, presents a case study demonstrating the application of the structured economic modeling and analysis framework for cost-effective and efficient management, rehabilitation and replacement of wastewater collection networks.

High quality condition assessment data is collected from the City of Niagara Falls wastewater collection network using the Side Scanner and Evaluation Technology. The data is condition coded and analyzed using Water Research Centre, UK, condition assessment protocols. A 50 year planning horizon is considered for five example management scenarios, namely: (1) do-nothing; (2) status quo; (3) replace pipes in Internal Condition Grade (ICG) 5; (4) renovate ICG 4 pipes and replace ICG 5 pipes; and (5) include ICG 3 pipes along with ICG 4 and ICG 5 pipes in the maintenance, renovation and replacement plan. A new ordinal regression model based on cumulative logits predicts the condition of wastewater pipelines for the five management scenarios over the planning horizon. The uncertainty of key input variables, such as cost and discount rate, is quantified using probability distributions. A risk-based approach using Monte Carlo simulation is applied for comparing alternative management scenarios, and selecting the one that best meet the strategic objectives of the organization. The presented case study investigates the impacts of various management strategies on the condition of reinforced concrete (RC) wastewater pipelines at the City of Niagara Falls. The uncertainty in future cash flows is quantified and implications on life-cycle cost for RC pipes are examined.

It is estimated that the City can save up to $50M over the 50 year planning horizon by following a proactive maintenance, renovation and replacement plan (i.e., alternative 5) for RC sewers when compared to status quo (i.e., alternative 2). Do-nothing is the worst scenario in terms of risks and impacts on the system whereas maintaining status-quo is the most expensive option. It should be noted that the results must not be taken as a general rule for other wastewater collection networks.

The presented study is deemed to be versatile in several ways. First, the deterioration model and planning takes into consideration the ordinal nature of response data. Second, the specified methodology specifically addresses the uncertainty and risk in strategic financial planning due to input variables that are not known with certainty. Third, the need to properly characterize the distribution of decision metric or output variable is demonstrated.

The presented analyses and findings will improve decision making related to: (1) the development of long-term wastewater infrastructure management plans; (2) the commitment of resources; and (3) the establishment of defensible policies.

Keywords: Life-cycle cost analysis; Wastewater collection networks; Monte Carlo simulation; Deterioration modeling

9.2 Introduction

This paper is the second in a two part series. Part 1 detailed an economic analysis framework for strategic decision-making related to the maintenance, renovation and replacement (M,R&R) of wastewater collection pipelines. In particular, Part 1 discusses: (1) the wastewater pipelines condition assessment; (2) deterioration modeling; (3) economic principles and concepts; (4) consideration of risk and uncertainty; and (5) Monte Carlo simulation technique, for financial sustainability planning of wastewater collection systems. This paper presents an overview of literature on economic analysis and life-cycle costing for civil infrastructure M,R&R. The application of the proposed structured framework is demonstrated using high quality condition assessment data collected by the authors from the City of Niagara Falls wastewater collection system. Five example management scenarios – namely, do-nothing, status-quo, replace ICG (internal condition grade) 5 pipes, renovate ICG 4 pipes and replace ICG 5 pipes, and renovate ICG 3 and ICG 4 pipes, and replace pipes in ICG 5 – are considered. The deterioration behaviour of Reinforced Concrete (RC) wastewater collection pipelines is estimated using a new ordinal regression model based on cumulative logits. The deterioration model predicts the impact of five example management strategies on the condition of RC pipelines. A life-cycle cost analysis is carried out for a 50 year planning period in terms of *present value* of future costs. The use of Monte Carlo simulation is demonstrated to explicitly and quantitatively address uncertainty and risk in the decision-making process. Typical results of the performed analyses are presented and discussed.

9.3 Literature Overview

The literature review revealed different perspectives to life-cycle cost analysis for civil infrastructure. Shahata and Zayed (2008) used Monte Carlo simulation for repair, renovation and replacement of watermains. The watermains service life was represented using normal and lognormal distributions. Log-logistic and lognormal models were deemed to fit the two optimal rehabilitation scenarios. Shahata and Zayed (2008) did not carry out a risk comparison of selected rehabilitation strategies.

The rate-of-return and cost-effectiveness methodologies discussed and demonstrated in Haas et al. (2006) are one of several possible techniques for economic analyses. Haas et al. (2006) used hypothetical data to demonstrate rate-of-return methodology for comparing life-cycle costs of alternative pavement designs. To check the variation in net present values, Haas et al. (2006) used three discount rates. The cost-effectiveness methodology presented in Haas et al. (2006) used ordinary regression for deterioration modeling of sidewalks. The condition of sidewalks, like other civil infrastructure, is estimated using an ordinal scale, and therefore, the deterioration model presented in Haas et al. (2006) violates the normal regression assumptions. Zayed et al. (2002) demonstrated the application of economic analysis and Markov Decision Process for life-cycle cost analysis for steel bridge paint systems, and found contradicting results. Tighe (2001) used Monte Carlo simulation to characterize the distribution of life-cycle costs (LCC) for pavements. Tighe (2001) found that input variables such as material costs and pavement thickness, and output variable (i.e., life-cycle cost) follow lognormal distributions. Tighe (2001) then repeated the analysis assuming normal distributions for input and output variables and compared normally distributed LCC with that from the lognormal model. Tighe (2001) concluded that the assumption of normal distribution for variables resulted in overestimation of LCC and potential to overdesign a pavement. Salem et al. (2003) compared the LCC cumulative distribution plots for different construction alternatives for pavements, and reported the risk as the probability of LCC exceeding a pre-specified budget. Osman (2005) proposed a framework to investigate investment opportunities in privatized civil infrastructure and used internal rate-of-return (IRR) as the decision metric. Osman (2005) used hypothetical data and noted the difficulties of collecting meaningful data to quantify infrastructure investment benefits and to perform useful LCC analyses.

The work in strategic financial planning and the development of long-term financial plans for sustainable wastewater infrastructure management is scarce and still in its infancy. Burgess (1990) proposed a planning model for sewer system rehabilitation using Markov chains (for deterioration model) in conjunction with present worth analysis for multiple rehabilitation scenarios. Burgess (1990) reported an optimal strategy which called for replacement of all pipes facing imminent failure (represented as pipes in grade E) and rehabilitation of significantly deteriorated pipes (represented as pipes in grade D). Burgess (1990) did not discuss the strategy of including moderately deteriorated (i.e., grade C) pipes along with the pipes in grades D and E in the rehabilitation plan. Furthermore, Burgess (1990) did not perform risk comparison of the proposed alternatives. Wirahadikusumah et al. (1999) and Wirahadikusumah and Abraham (2003) used Markov Decision Process (MDP) and Probabilistic Dynamic Programming (PDP) to prioritize M,R&R (maintenance, rehabilitation and replacement) techniques for wastewater pipelines. The application of MDP and PDP was elaborated using cost estimates for 1.5 m diameter pipe in Indianapolis, USA. In particular, renovation alternatives, such as cleaning, shotcrete coating, cured-in-place pipe lining, fiberglass reinforced sliplining, and open-cut replacement, were considered for pipelines in particular structural condition grades of 1 to 5. The model output consists of an optimum policy for cost-effective M,R&R techniques at particular stages of the planning horizon and condition states. Wirahadikusumah et al. (1999) repeated the analysis for different planning horizons and estimated long-term rehabilitation costs. According to Wirahadikusumah and Abraham (2003), "optimal decisions vary with pipe diameter." Bainbridge and Macey (2005) discussed the application of a Markov chain deterioration model for the development of long-term budgets. The ratio of change in asset value to the net present value was considered as an indicator of the effectiveness of a particular rehabilitation strategy. The Sustainable Funding Model proposed by Bainbridge and Macey (2005) provides optimum funding levels for short and long-term rehabilitation plans. However, it did not take into account the risk and uncertainty related to input variables.

9.4 Objective and Problem Description

For a wastewater utility, one of the infrastructure management strategic objectives can be defined as *to provide safe and reliable wastewater collection services at the minimum long-term costs.* To achieve this objective, life-cycle costs of alternative M,R&R strategies need to be investigated keeping in view the uncertainty and risk due to changes in input variables, such as costs, work quantities, and economic conditions over the planning horizon. The output of the analysis consists of an economic *decision metric* e.g., *present worth of future* *net costs* that provides an estimate of long-term monetary requirements to maintain, renovate and replace existing wastewater pipelines. The proposed framework from Part 1 is applied to address the following specific questions at the network level:

1. How alternative management strategies will impact network condition over the life-cycle analysis period?

2. What are the life-cycle financial implications of the proposed management scenarios – that is, the impact of renovation and replacement work quantities on cash flows and costs?

3. What funding level is required to get the network to a sustainable level? and

4. What happens if economic conditions, e.g., interest rate, change over the life-cycle analysis period?

A tacit assumption is that the estimated quantity of work under a selected alternative is manageable from operational perspectives and within the specified time period. Figure 9.1 illustrates the methodology for Monte Carlo based financial simulation modeling used in this research. The methodology is further described in the following sections (for illustration, only reinforced concrete (RC) pipes are considered in the economic analysis).

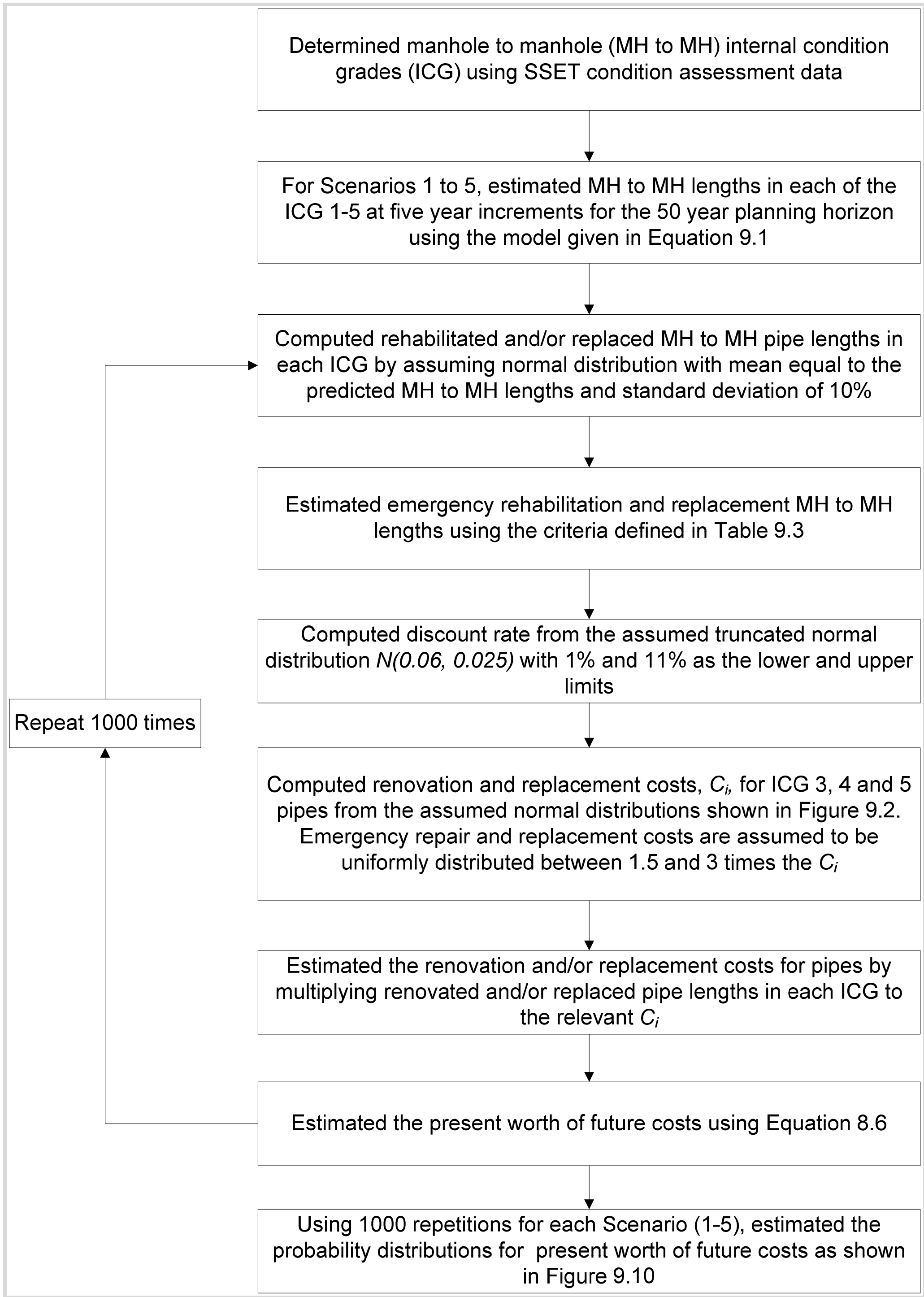

Figure 9.1: Flowchart Illustrating the Methodology for Economic Analysis

9.5 City of Niagara Falls Pipeline Condition Assessment Data

The City of Niagara Falls wastewater collection network consists of approximately 400 Kms of pipelines that has approximately 5,500 pipe segments consisting of a variety of pipe materials with age ranging from 10 to over 100 years. The average age of the network is 47 years. The distribution of various pipe materials is as follows: 35% of the network consists of Reinforced Concrete (RC); 17% PVC; 10% Vitrified Clay (VC); 10% Asbestos Cement (AC); and 25% of the network has no assigned pipe material. The average age of the RC and VC pipes are 42 and 65 years, respectively.

Wastewater pipelines' inspections were carried out using the Side Scanner and Evaluation Technology (SSET) camera. Water Research Centre's (WRc) protocols as detailed in the Manual of Sewer Condition Classification (MSCC, 3rd ed.) and Sewerage Rehabilitation Manual (SRM, 4th ed.) were used for pipelines condition assessment. A contractor supplied North American Association of Pipelines Inspectors (NAAPI) certified operator completed all the SSET pipeline surveys, and coded all pipeline defects in accordance with the MSCC. The NAAPI certified City of Niagara Falls personnel and authors carried out additional Quality Assurance (QA) and Quality Control (QC) checks on all the contractor provided data.

The quality pipeline inspection data from the City of Niagara Falls was transported to the University of Waterloo to be stored on two geographically distributed data servers. The servers are backed-up using RAID 5 technology to ensure data security, availability, and seamless recovery. Using a University of Waterloo custom built software application, the

City of Niagara Falls QA/QC data is uploaded into a database management system named WatBAMS (Waterloo – Buried Asset Management System). The software import utility contains further QA/QC protocols to ensure that only high quality data is uploaded in the database for each inspected pipe segment. Using programmed routines in WatBAMS, each pipe segment is analyzed in accordance with the Sewerage Rehabilitation Manual (4th edition) methodology to determine its Internal Condition Grade (ICG). WatBAMS also allows for the upload and integration with the City's of Niagara Falls GIS and inventory database that contain each pipe segment's attributes, e.g., asset ID, location, construction date, and material type, etc.

9.6 Deterioration Model

Approximately 12% (45 Kms) of the City of Niagara Falls wastewater collection network data is used in the model development. The detailed procedure for model development, evaluation, and analysis is discussed in Younis and Knight (2009). Equation 9.1 presents the functional form and Table 9.1 provides the parameter estimates of the proposed deterioration model. The deterioration model is developed for reinforced concrete and vitrified clay pipes; however, only reinforced concrete pipes are considered in the analyses and discussion presented in this paper.

$$\text{logit}\left[\hat{P}\left(Y \le j \mid \text{material}, \text{age}, \hat{\mu}, \hat{\beta}\right)\right] = \hat{\mu}_j - \hat{\beta}_1 \text{material} - \hat{\beta}_2 \text{age} - \hat{\beta}_3 \text{material} \times \text{age} \quad (9.1)$$

Figure 9.2 shows the predicted probabilities of being into one of the five ICG (internal condition grades) with *age* for reinforced concrete wastewater pipelines at the City of

Niagara Falls. The probabilities of the lowest and highest response categories (i.e., ICG = 1 and ICG = 5) are monotonic functions of *age*, whereas, the probabilities of the intermediate categories (i.e., ICG = 2, 3, and 4) are unimodal or single-peaked functions.

The effect of *age* on the probability of being in ICG 1 is negative i.e., the probability of a pipeline being in acceptable condition decreases with the *age* of pipe. On the other hand, the effect of *age* on the probability of being in grade 5 is positive, i.e., the probability of a pipeline being in grade 5 increases with *age*. The predicted probabilities of being in intermediate grades first increase with *age*, and then decrease after certain *age* thresholds. For example, in Figure 9.2, the probability of being in ICG 3 first increases until the age of about 55 years and then decreases for RC pipes. This occurs because as the age increases, more cases move into ICG 3 than leave from ICG 3 to other worse categories. Therefore, the probability of being in ICG 3 increases. As the age is increased beyond 55 years, cases entering ICG 3 are less than the cases leaving, thus the probability decreases.

Table 9.1: Deterioration Model Parameter Estimates

Variable	**Coeff.**	**Std. Err.**	**z**	**P>z**	**[95% Conf. Interval]**	
material, β_1	-3.439	0.633	-5.430	0.000	-4.680	-2.198
age, β_2	0.008	0.007	1.220	0.223	-0.005	0.022
age x material, β_3	0.046	0.011	4.190	0.000	0.025	0.068
cut1, μ_1	-0.714	0.514			-1.721	0.294
cut2, μ_2	-0.352	0.512			-1.356	0.652
cut3, μ_3	0.199	0.512			-0.804	1.203
cut4, μ_4	1.491	0.528			0.456	2.527

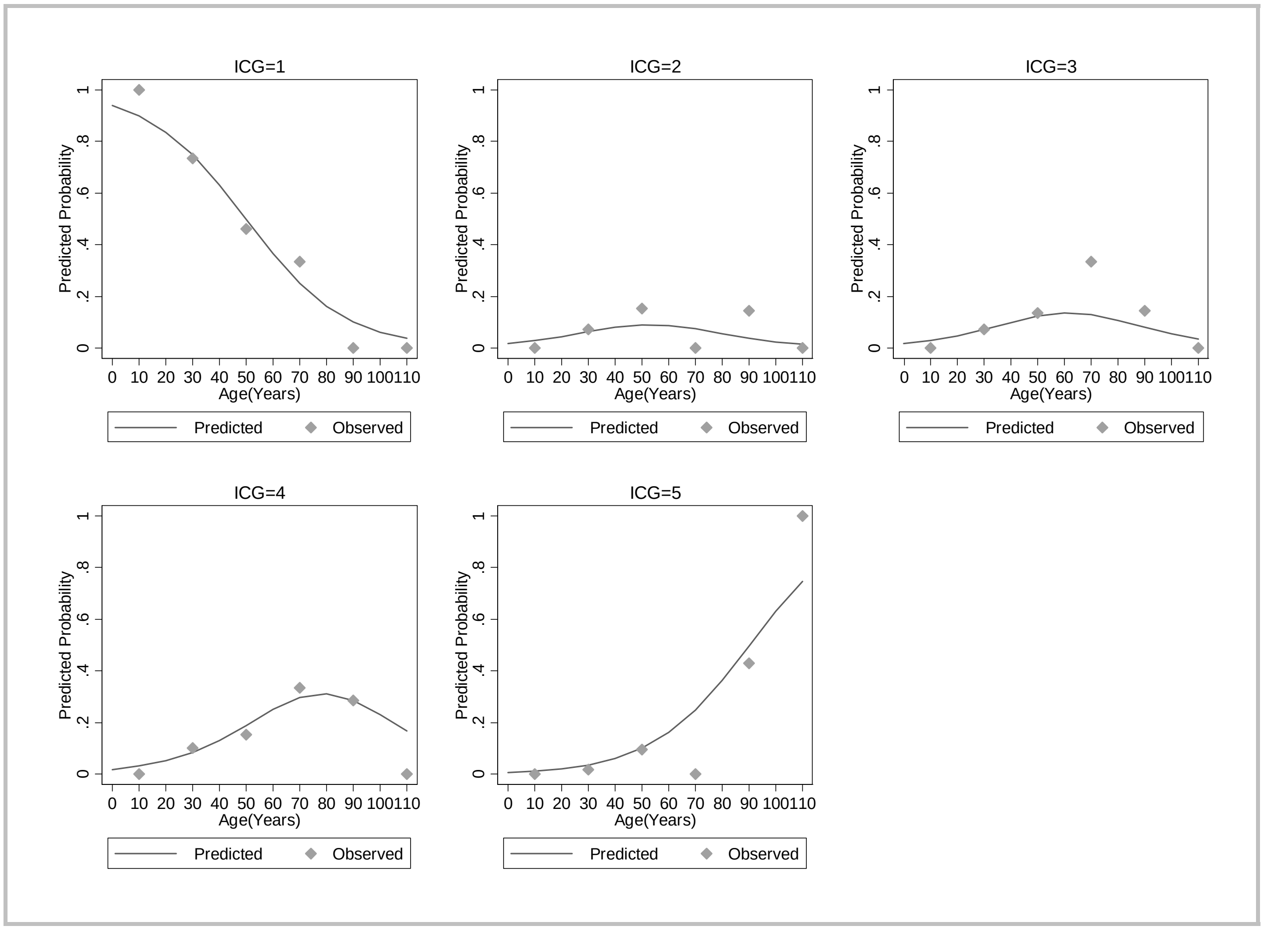

Figure 9.2: Predicted Probabilities for RC Pipes

9.7 Economic Analysis

The deterioration model predicts the RC wastewater pipeline lengths in ICG (internal condition grades) 1 to 5 with *age* for each of the five management scenarios presented in Table 9.2.

Table 9.2: Management Scenarios

Scenario S1:	Do-nothing – that is, allow the network to deteriorate without performing M,R&R (maintenance, rehabilitation and replacement) activities. This strategy will result in potential savings as no money is spent on condition based scheduled M,R&R activities for ICG 3, 4, and 5 pipes. However, there are consequences of following this strategy that may include: (1) accidents; (2) sewer backups resulting in overflows and property damages; (3) environmental hazards, e.g., soil and groundwater contamination; and (4) health hazards and deaths. Therefore, ER&R (emergency repair and replacement) costs and liabilities will add up with time.
Scenario S2:	Perform adequate renovation and replacement activities to maintain the system at the current service level over the analysis period. This scenario involves the estimation of quantities and financial resource requirements to keep the percentage of ICG 5 pipe at the existing level over the planning horizon.
Scenario S3:	Replace only the ICG 5 pipes during the life-cycle analysis period.
Scenario S4:	Renovate and replace ICG 4 and 5 pipes over the planning horizon.
Scenario S5:	Include ICG 3 pipes along with ICG 4 and 5 pipes in the maintenance, renovation and replacement plan.

The scenarios S2-S4 will save M,R&R costs, but ER&R costs can increase with time. This is further discussed in Section 9.7.1 (Table 9.4). The uncertainty in present worth of future costs under the five management scenarios is estimated using Monte Carlo simulations. The Monte Carlo method samples the entire solution space, and therefore, better handles the uncertainty (Emblemsvag, 2003).

9.7.1 Input Variables

Important input variables include the following:

1. Rehabilitation Costs

The sampled data in the presented study consists of pipes with diameter ranging from 250 mm to 750 mm. Bainbridge and Macey (2005) and Leung et al. (2007) reported average manhole-to-manhole renovation costs per meter of pipe length at various stages of deterioration cycle for the wastewater collection systems at the Cities of Winnipeg and New Westminister, Canada. It is noted that Bainbridge and Macey (2005) and Leung et al. (2007) used a combination of six manhole-to-manhole rehabilitation work streams for condition grades of 3, 4 and 5. Table 9.3 provides their estimated average renovation/replacement costs in each condition grade for pipes with diameter ranging from 150 mm to 1200 mm. Bainbridge and Macey (2005) and Leung et al. (2007) further noted that the reported cost estimates did not include emergency repairs and that the costs were *not* affected by pipe diameter.

Zhao and Rajani (2002) reported costs of rehabilitation and construction projects for buried pipes. They concluded that trenchless rehabilitation costs tend to increase with pipe diameter and emergency repairs can cost three times the scheduled repair costs. MacLeod et al. (2000) performed an analysis of historical repair cost data for the wastewater collection network at the City of Edmonton, Canada. According to their analysis, the mean emergency repair cost was 55% greater than the scheduled repairs and its variance was three times higher than that of the scheduled repairs.

Wirahadikusumah and Abraham (2003) considered renovation alternatives, such as cleaning, shotcrete coating, cured-in-place pipe lining, fiberglass reinforced sliplining, and open-cut replacement, at unit costs of $16/m, $656/m, $1,558/m, $2,231/m, and $1,066/m, respectively, for 1500 mm diameter pipelines in various condition grades. Wirahadikusumah and Abraham (2003) estimated optimal rehabilitation costs of $377/m, $719/m, $1,145/m, $1,703/m and $1,421/m for pipes in structural grades 1, 2, 3, 4 and 5, respectively for the general case.

Table 9.3 shows the *intervention ratios* – that is, the ratios of renovation costs in intermediate internal condition grades to the cost in ICG (internal condition grade) 5 – for rehabilitation costs at ICG 3 and ICG 4. Bainbridge and Macey (2005) and Leung et al. (2007) concluded that intervention ratios roughly follow one-third and two-third rule – that is, rehabilitation costs at ICG 3 and ICG 4 are one-third and two-third of cost at ICG 5.

For this study, average intervention costs of $1000, $700, and $300 are assumed for scheduled replacements and repairs of pipelines in ICG 5, 4, and 3, respectively. The ER&R (emergency repair & replacement) costs are assumed to vary from 1.5 to 3 times the costs for scheduled repairs/replacements. These cost estimates are in line with the assertions made by Bainbridge and Macey (2005) and Leung et al. (2007). To model cost uncertainty, a normal distribution is assumed. Figure 9.3 shows the cost distribution with mean values of $1000, $700, and $300 for pipes in ICG 5, 4 and 3, respectively.

Table 9.3: Rehabilitation Costs (adapted from Bainbridge and Macey, 2005; Leung et al. 2007)

Condition Grade	Winnipeg		New Westminister	
	Cost/meter/MH-to-MH Segment	Intervention Ratio	Cost/meter/MH-to-MH Segment	Intervention Ratio
5	$841	1.00	$416	1.00
4	$604	0.72	$279	0.67
3	$241	0.29	$144	0.34

A uniform distribution is assumed to quantify the uncertainty in ER&R costs. Social costs such as traffic disruptions due to a particular renovation/replacement technique and property damages from sewer overflows and blockages are assumed to be included in ER&R costs.

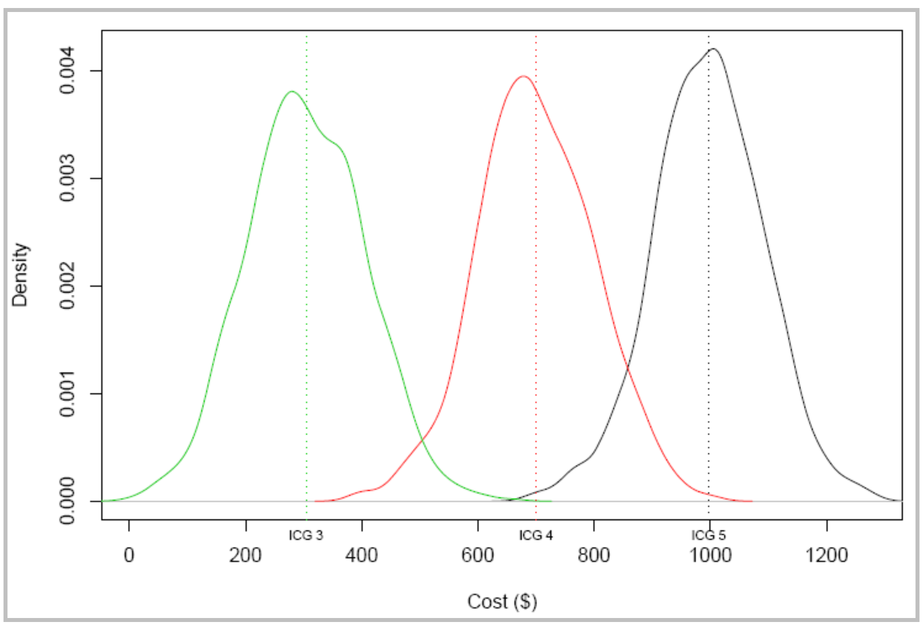

Figure 9.3: Renovation/Replacement Cost Distributions in Internal Condition Grades (ICG) 3, 4 and 5

2. Interest Rate and Inflation

Average interest rate (discount rate) of 6% is assumed to relate future cost estimates to present worth. According to Hudson et al. (1997), many agencies use *inflation adjusted discount rate* – that is, the difference between borrowing or investing interest rate minus inflation – for comparing infrastructure investment alternatives. Hudson et al. (1997) argued that "inflation should only be used for setting real discount rates" in economic analysis for infrastructure management systems, and that considering inflation as an additional factor does not result in better selection of alternatives. The study by Wirahadikusumah and Abraham (2003) found that optimal maintenance and rehabilitation alternatives were not affected by inflation and interest rates. Figure 9.4 shows uncertainty distribution – a truncated Normal – for discount rate, $i \sim N(.06,.025)$ with 1% and 11% as the lower and upper bounds.

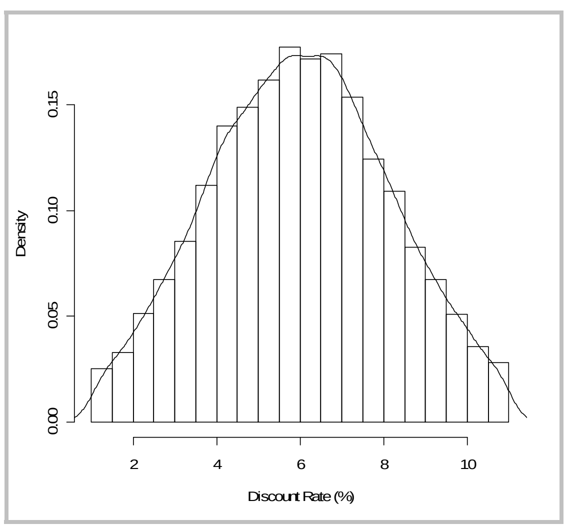

Figure 9.4: Discount Rate, $i \sim N(6\%,.025)$

3. Rehabilitated/Replaced Pipe Lengths (i.e., Quantity of Work to be Carried Out)

The proposed deterioration model (see Section 9.6) is used to estimate the pipe lengths to be rehabilitated or replaced during five year periods over the life-cycle planning horizon of 50 years. Table 9.4 provides additional information about how the pipe lengths for each of the five management scenario are computed.

Table 9.4: Management Scenarios and Assumed Pipe Lengths for Renovation and Replacement

Management Scenario	Description	Pipe Lengths Renovated and/or Replaced
1	Do-nothing	Emergency Repairs and Replacements (ER&R): assumed Uniform distribution with 50-100% of ICG 5, 30-70% of ICG 4, and 5-20% of ICG 3 pipe lengths may need ER&R
2	Status quo i.e., maintain the system in its current condition	Predicted length in ICG 4 and 5 $\pm$ 20%. Assumed Uniform distribution with 30-70% of remaining ICG 4 and 5-20% of ICG 3 pipes may need ER&R
3	Replace ICG 5 pipes	Predicted length in ICG 5 $\pm$ 20%. Assumed Uniform distribution with 30-70% of ICG 4 and 5-20% of ICG 3 pipes may need ER&R
4	Renovate and replace ICG 4 and 5 pipes	Predicted length in ICG 4 and 5 $\pm$ 20%. Assumed Uniform distribution with 5-20% of ICG3 pipes may need ER&R
5	Renovate and replace ICG 3, 4 and 5 pipes	Predicted length in ICG 3, 4 and 5 $\pm$ 20%

4. Planning Horizon

The analysis is based on a life-cycle period of 50 years as suggested by Hudson et al. (1997) for wastewater collection pipelines.

9.7.2 Output Variable or Decision Metric

The decision metric or the output variable is the Present Worth (PW) of future net costs (i.e., cost minus savings). One thousand trials of Monte Carlo simulation were performed and present worth of future net costs are estimated for the five management scenarios using present worth formula and rate-of-return factors as presented in Section 8.4.3.

9.8 Results

Figures 9.5 to 9.9 show the estimated RC pipe lengths in each ICG with time over the life-cycle analysis horizon for the five M,R&R scenarios.

Figure 9.5 shows the predicted lengths of RC wastewater pipelines for the case, S1, when no rehabilitation or replacement work is carried out over the 50 year life-cycle analysis period. The deterioration trend corresponds to the predicted probability chart shown in Figure 9.2. The predicted lengths in ICG 3 and 4 first increase and then decrease with age whereas the predicted lengths in ICG 5 continue to increase. At time 0, the estimated lengths of RC pipelines in ICG 3, 4, and 5 are 13.4 Kms, 18.7 Kms, and 9.6 Kms, respectively. If no renovation and replacement is performed over the next 50 years, the predicted lengths in ICG 3, 4 and 5 will be 10.5 Kms, 36.3 Kms and 68.3 Kms, respectively. The percentage increase in ICG 5 pipes is 611% $\left[i.e., \left(68.3-9.6\right)/9.6 \right]$ in 50 years.

Figure 9.6 shows the status quo scenario, S2, – that is, just enough renovation and replacement work is performed to keep the system in its current condition over the life-cycle analysis period. Specifically, the percentage of RC pipe length in ICG 5 is maintained close to the current value of 7% (9.6 Kms) of the total RC network over the next 50 years. In Figure 9.6 bars show the predicted pipe lengths in ICG 3, 4 and 5 with time, whereas, the connected lines show the quantity of work needs to be carried out in ICG 4 and 5 to accomplish the objective of this strategy. For example, from time 0 to 5 years, 9.6 Kms of ICG 5 pipe length needs to be replaced along with renovation of 12 Kms of ICG 4 pipe length. Renovation of ICG 4 pipe length during 0-5 year period ensures that the predicted ICG 5 pipe length in the 5-10 year period does not exceed the pre-set limit of 9.6 Kms. Figure 9.6 shows that 100% of the predicted ICG 5 pipe length (approximately 9.6 Kms) will need to be replaced during each five year period for the next 25 years. After 25 years, the required ICG 5 pipe replacement length decreases to about 6 Kms for each five year period for the next 10 years. From years 35 to 50, the quantity of work to be performed in ICG 5 decreases steadily from 5 Kms to 3 Kms per five year period. The quantity of rehabilitation work on ICG 4 pipes decreases from 12 Kms per 5 year during the 0-10 year period to 0 Kms after 25 years.

Figure 9.6 shows scenario S3, where only the estimated ICG 5 pipe lengths will be replaced over five year periods during the planning horizon. Under this scenario, approximately 9.6 Kms length (shown at year 0) will be replaced in the first five years, 11 Kms (shown at year 5) will be replaced from 5-10 year period, and the process will continue over the life-cycle analysis horizon of 50 years. The estimated pipe replacement requirement starts decreasing after 35 years of age. By year 50, about 120 Kms $\left[120/134.9 = 89\%\right]$ length of RC pipes will be replaced. This represents an average replacement rate of 2.4 Kms per year.

Figure 9.8 presents scenario S4 and shows the estimated required renovation and replacement pipe lengths in ICG 4 and 5 with time. At year 0, the estimated lengths of RC pipes in ICG 4 and 5 are 18.7 Kms and 9.6 Kms, respectively. These lengths are renovated and replaced from 0-5 year period. Figure 9.8 shows that approximately 3.7 Kms of RC pipes will be in ICG 4 and 2.7 Kms will be in ICG 5 after 35 years – that is, less than 5% $\left[i.e., (3.7 + 2.7)/134.9\right]$ of RC pipelines are estimated to be in ICG 4 and 5 under this management scenario.

Figure 9.9 shows the estimated renovation and replacement requirements with time under scenario S5. This scenario is similar to S4 with the exception that ICG 3 pipes are also considered in the maintenance, rehabilitation and replacement plan along with ICG 4 and 5 pipelines. Under this alternative, the ICG 4 and 5 pipe lengths reduce at a much faster rate than other scenarios. For example, from 5-10 year period, 7.7 Kms of pipes need to be replaced in this scenario as compared to scenario S4 where approximately 9 Kms of pipes will need replacement during the same time period. In 25 years, less than 5% of the RC pipes in the network will be in ICG 4 and 5 under this strategy.

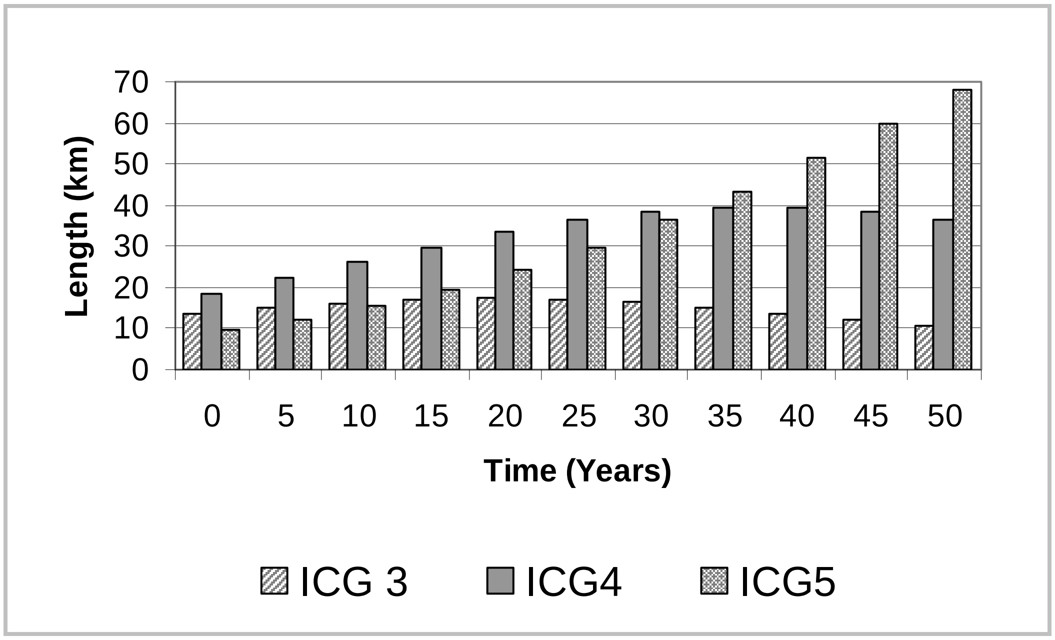

Figure 9.5: Scenario S1 – Do Nothing (No Rehabilitation/Replacement Work Performed) RC Pipelines' Predicted Lengths

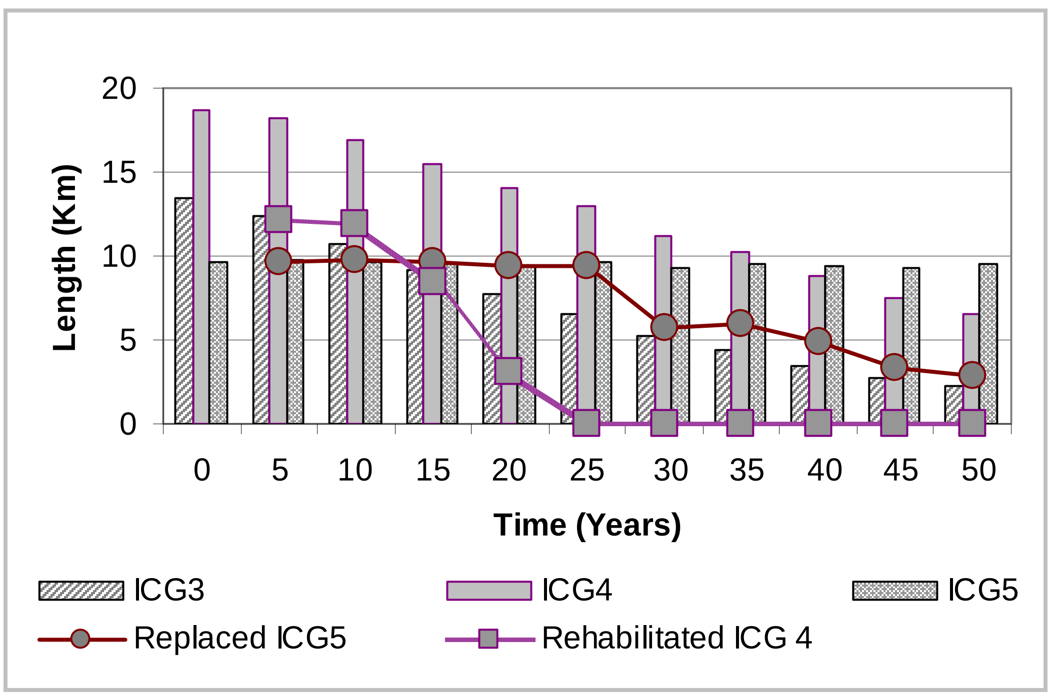

Figure 9.6: Scenario S2 – Predicted, Rehabilitated and Replaced RC Pipes' Length to Sustain Current Network Condition

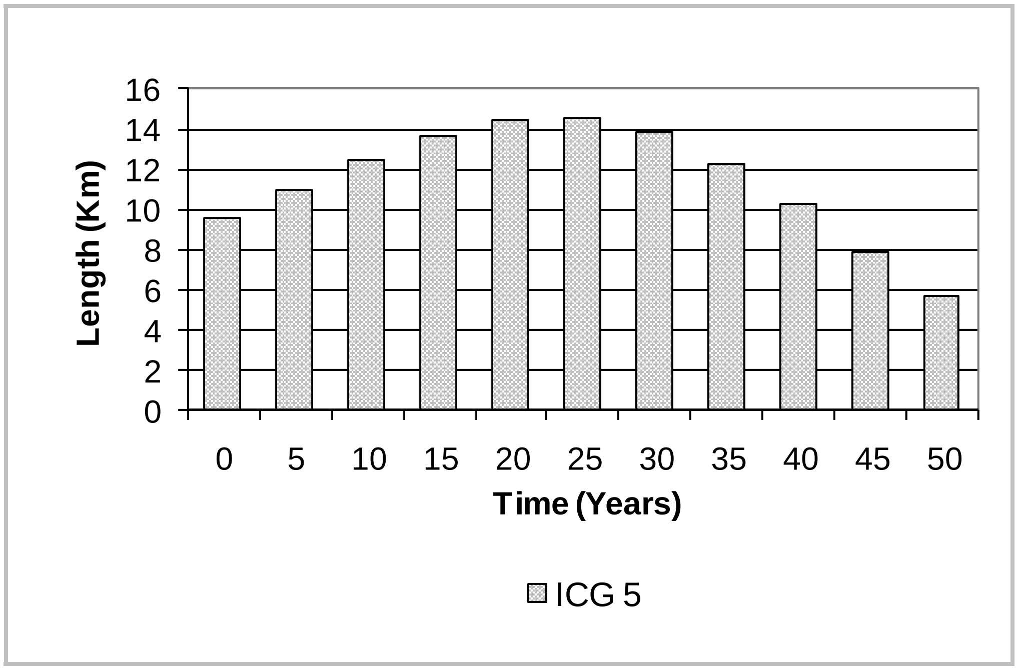

Figure 9.7: Scenario S3 – Predicted ICG 5, RC Pipes' Length to Be Replaced

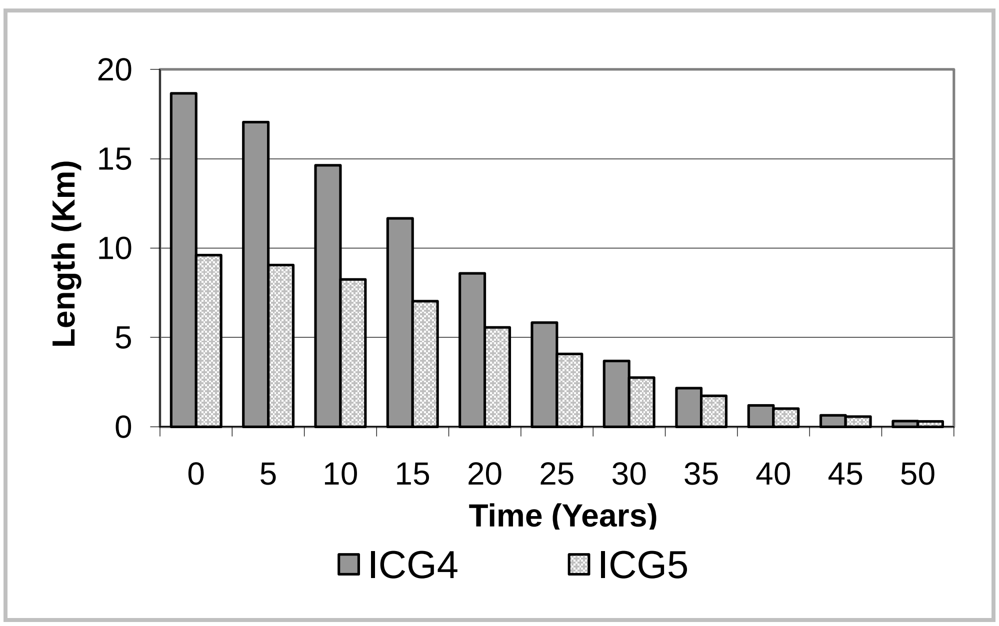

Figure 9.8: Scenario S4 – Predicted ICG 4 and 5, RC Pipes Length to be Renovated and Replaced

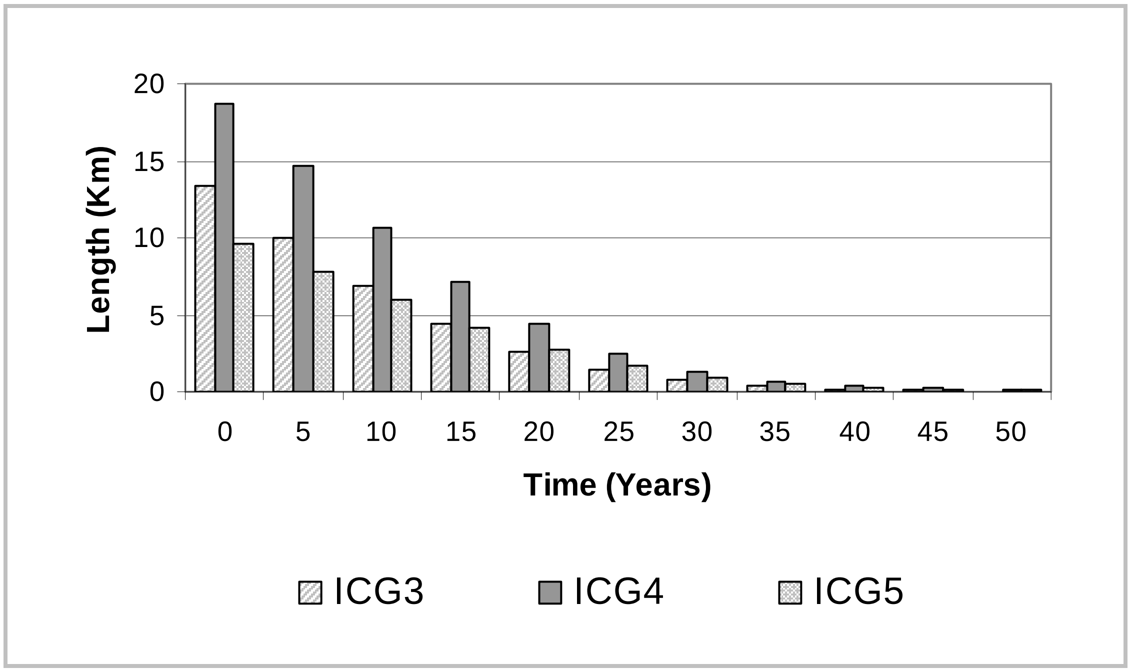

Figure 9.9: Scenario S5 – Predicted ICG 3, 4 and 5, RC Pipes' Length to be Renovated and Replaced

Figure 9.10 shows a single simulation run of estimated cash flows for the future rehabilitation and replacement *net costs* – that is, the difference between M,R&R costs (including emergency intervention costs) and the savings from deferring maintenance – for the five management scenarios. The estimated costs, in case of scenario S1, are initially lower than the costs in rest of the scenarios, but surpass them after about 15-20 years. The costs for scenario S5 are higher in the beginning when compared to scenarios S1, S3 and S4 but fall below the other scenarios after about 15 years. Figure 9.10 shows that the estimated future costs will increase to $70 M in 50 years in case of do nothing strategy, whereas, the estimated future costs decrease under the rest of the alternatives.

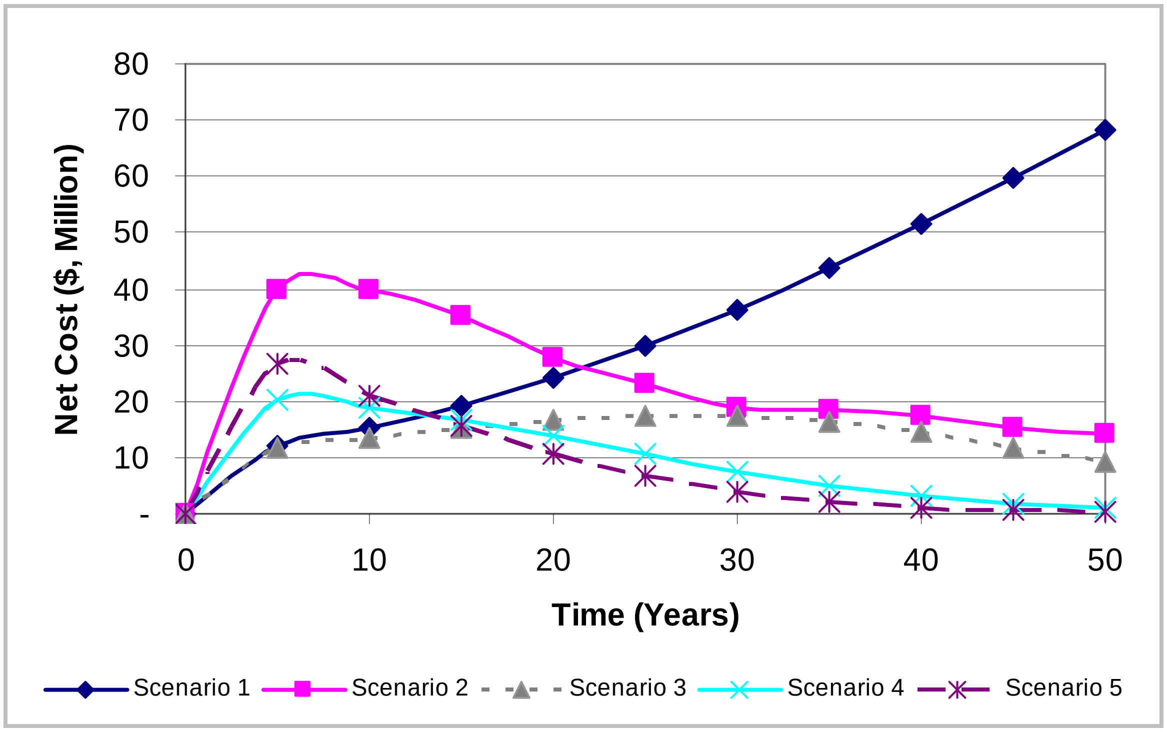

Figure 9.10: Estimated Future Net Cost Cash Flows

Figure 9.11 shows the distribution plots of Present Worth (PW) of future net cash flows for the five example scenarios. It is noted that PW distributions for scenarios S1 and S2 are highly skewed to the right, whereas for scenarios S3, S4 and S5, they are mildly skewed. This means that the estimated PW are not normally distributed. To confirm this, Figure 9.12 shows the normal Q-Q plots for PW values from five alternatives. The plots show that the point pattern is not linear but is curved with slope increasing from left to right for scenarios S1, S2, S4 and S5. This indicates a right skewed distribution with estimated PW values greater than zero. For S3, the left end of the pattern is above the line and right end is below the straight line. This indicates symmetric, short tails at both ends. These patterns are further evident from Figure 9.13 that shows the histograms of PW values with lognormal curve overlays for the five alternatives. According to Limpert et al. (2001), lognormal distribution closely fit to the data that is greater than zero, skewed to the right, and have low mean values but large variances. The lognormal Q-Q plots (also shown in Figure 9.13) reveal a linearized point pattern (except beyond 99th percentile) for the five scenarios when the simulated PW data is modeled using lognormal distribution. Therefore, lognormal distribution provides a reasonable fit. It may be noted that a three-parameter lognormal distribution is used to model PW values. The three-parameter lognormal distribution includes an additional threshold parameter, θ, that determines the lower bound and allows a shift along *x*-axis without affecting the variance or shape of distribution (McBride, 2005; Millard, 2001; Pearson, 2002). McBride (2005) noted that for lognormal distribution, sample mean is biased whereas sample median (geometric mean) is an unbiased estimate of its population value. The median and mean for the three-parameter lognormal distribution can be calculated using the following expressions (McBride, 2005):

$$\text{median(=geometric mean)} = \exp\left(\xi\right) + \theta$$
$$\text{mean} = \exp\left(\xi + \sigma^2/2\right) + \theta$$

where ξ and σ are the mean and standard deviation of the logarithms of PW values and θ is the threshold/shift parameter. Table 9.5 presents the estimated model parameters for the five example scenarios.

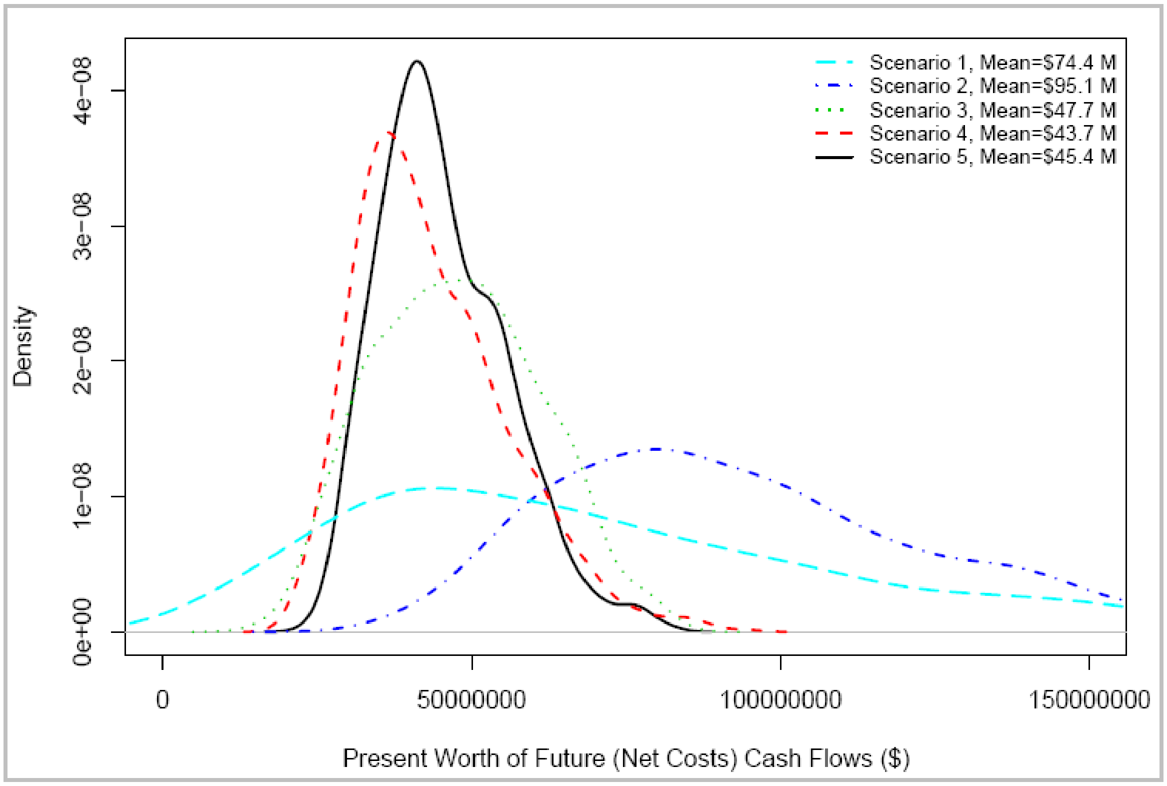

Figure 9.11: Present Worth of M,R&R Costs Under Five Management scenarios

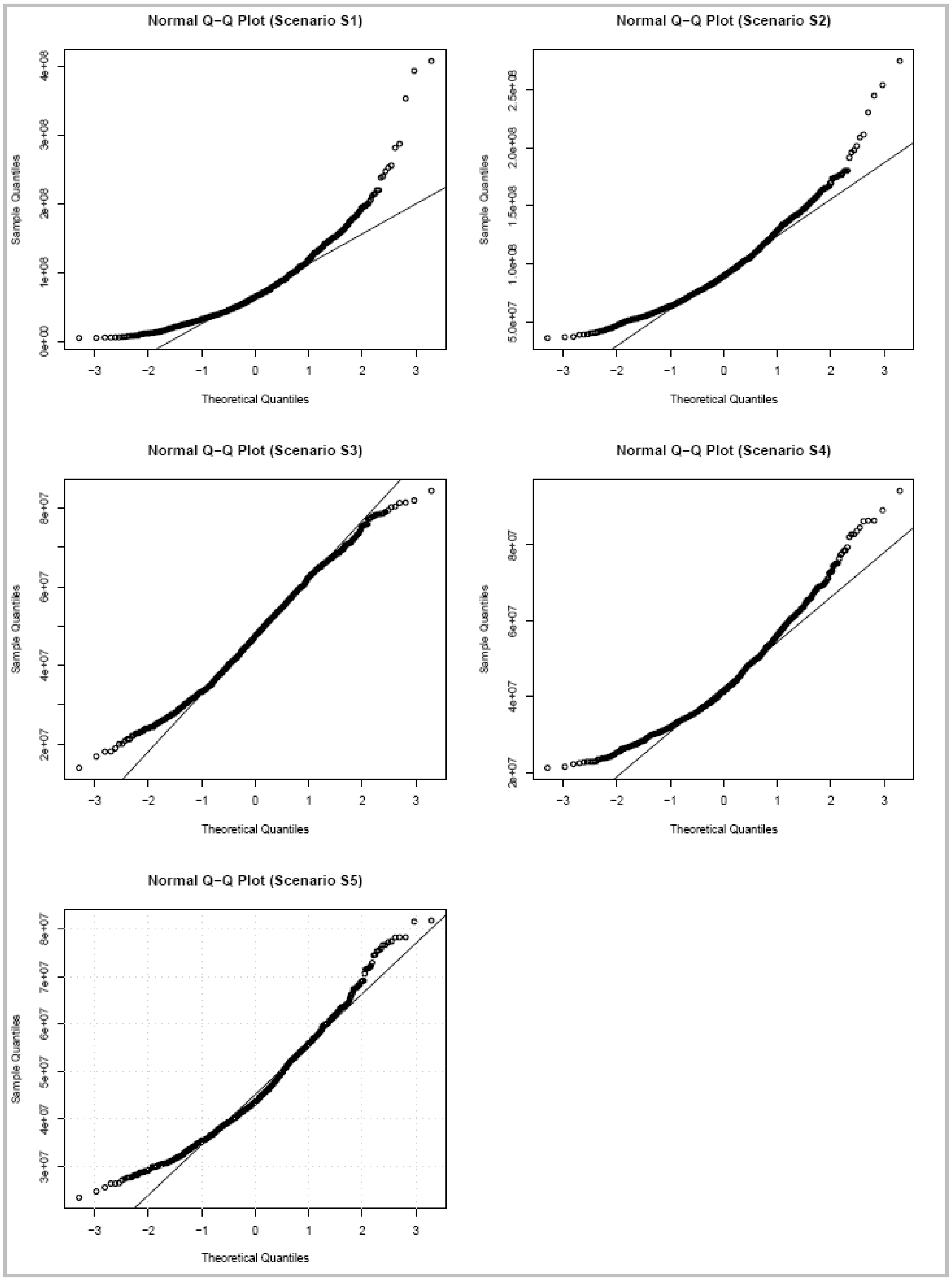

Figure 9.12: Quantile Plots for PW for Five Management Scenarios

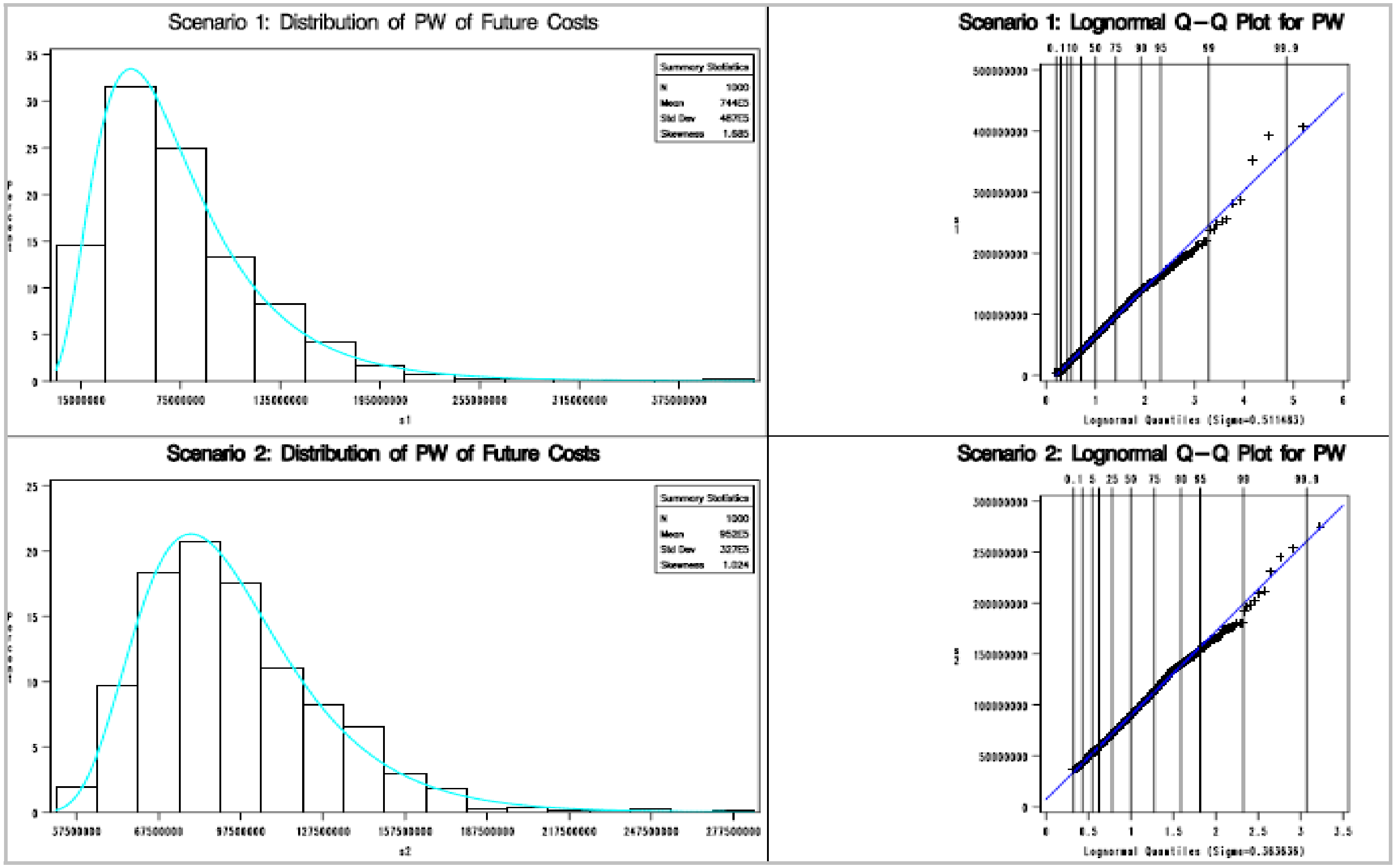

Figure 9.13: Lognormal Model Fit for Present Worth of M,R&R Alternatives

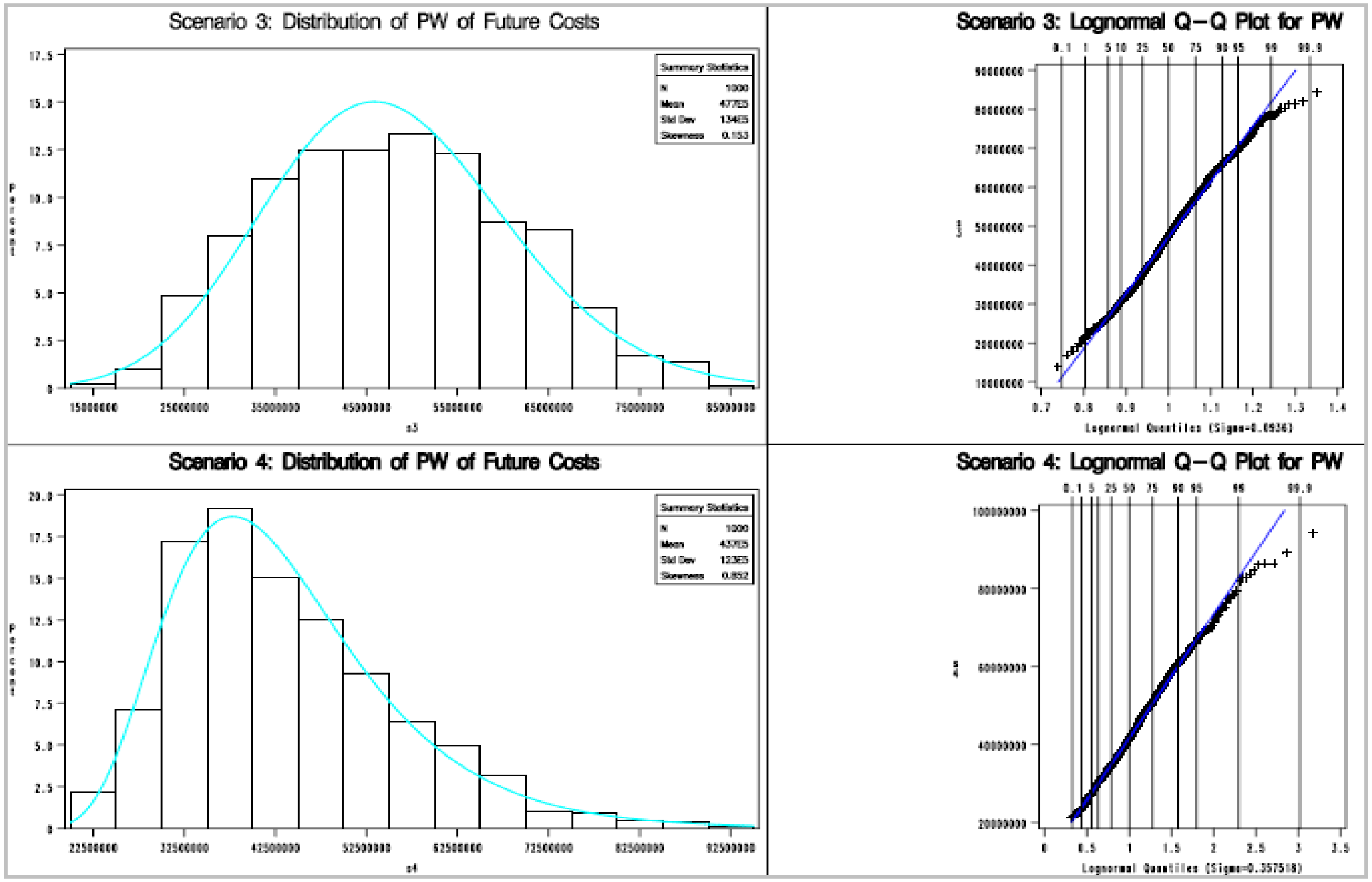

Figure 9.13 (Cont'd)

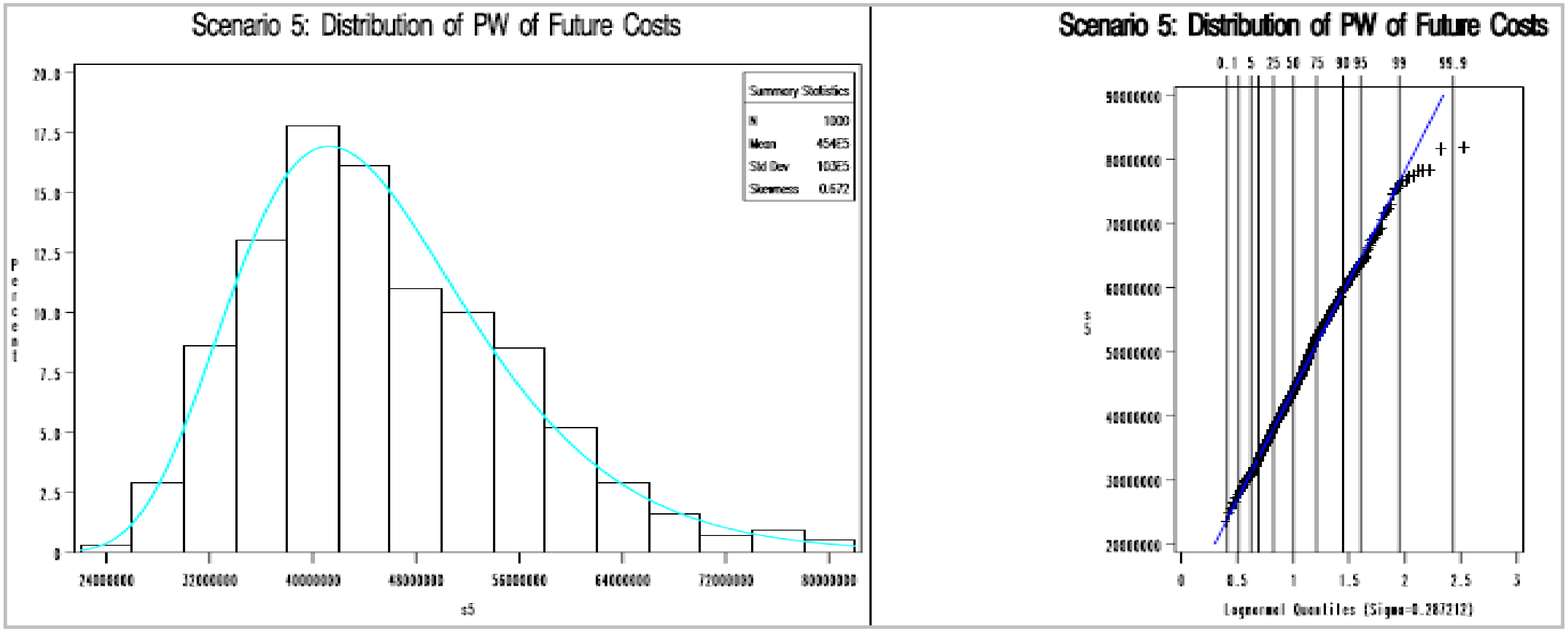

Figure 9.13 (Cont'd)

Table 9.5: Lognormal Model Estimated Parameters for the Five Scenarios

Scenario	Threshold θ	Scale ξ	Shape σ	Mean, μ ($ M)	Std. Dev., s ($ M)	Median (Geometric Mean) ($ M)	Multiplicative Confidence Interval ($ M) [68.3%]
1	-1.63E+07	18.193	0.511	74.5	49.7	63.3	[31.4,116.5]
2	7083444	18.228	0.364	95.2	33.1	89.6	[64.4, 125.8]
3	-9.54E+07	18.775	0.094	47.7	13.4	47.1	[34.4, 61.1]
4	9819420	17.275	0.358	43.7	12.5	41.6	[32.1, 55.3]
5	9758398	17.348	0.287	45.4	10.5	43.9	[35.4, 55.3]

Figure 9.14 and Figure 9.15 provide overall summary of the results. In this thesis, *risk* is defined as the variance of the decision metric as noted in Kühn (2006). This method of defining risk is commonly used in the investment finance literature – see the modern portfolio theory and efficient frontier (Gallati, 2003; Strong, 2000). *Efficient frontier* represents mean-variance efficient combinations where a plot of expected return versus risk of possible investment opportunities is created for investors to select the desired risk-return combination. Using this concept, Figure 9.14 plots the expected PW and standard deviations for the five example scenarios and provides a risk comparison.

The scenario S1 is economical when compared to scenario S2 – that is, expected PW of future costs for scenario S1 (i.e., $ 74.5 M) is less than that of scenario S2 (i.e., $95 M). – but, scenario S1 is riskier than scenario S2 as the measure of dispersion for S1 (i.e., 49.7 M) is more than that of S2 (i.e., 33.1 M). The deferred maintenance reduced the present value of future net costs, but increased the variability that shows significant risk and impacts on the system. Figure 9.14 shows that S1 is the most risky strategy (Std. Dev. = $49.7 M), whereas S5 is the least risky one (Std. Dev. = $10.5 M). Scenario S4 is the least cost alternative (i.e., $43.7 M), whereas the scenario S2 has the highest cost (i.e., $95.2 M).

Figure 9.15 shows the risk profiles of estimated PW values for scenarios S3, S4 and S5 (scenario S1 and S2 are dropped because of high expected PW and risk values). The vertical scale in Figure 9.15 represents the probability of exceeding various levels of PW. For example, there is 50% probability that the PW of future costs will be between $40M and $50M under scenarios S3, S4, and S5. The slopes of the plot represent the risk in terms of variability – that is, flatter the slope, higher the risk. Scenarios S3, S4 and S5 are close to each other, and the estimated PW and standard deviation appear to be indistinguishable. To verify if the difference between estimated PW values for scenarios S4 and S5 is statistically significant, two non-parametric tests, namely, Mann-Whitney Two Sample Rank-Sum Test and Median Test are performed. Unlike the Independent-Samples *t* test, Mann-Whitney Two Sample Rank-Sum Test and Median Test do not require the dependent variable to have normal distribution (Chatfield, 1995; Schlotzhauer, 1987).

Mann-Whitney Two Sample Rank-Sum Test assesses the hypothesis that two independent samples of data have identical distributions. The results presented in Table 9.6 show that the Wilcoxson statistic equals 942216.

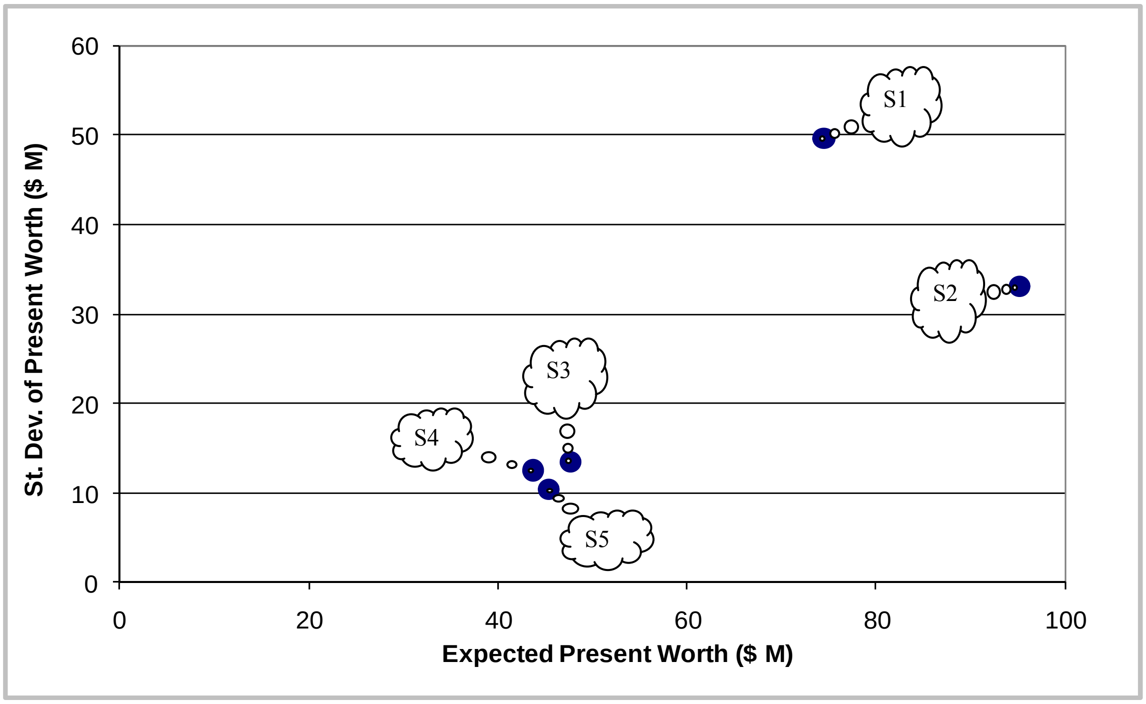

Figure 9.14: Risk Comparison of Five Management Scenarios

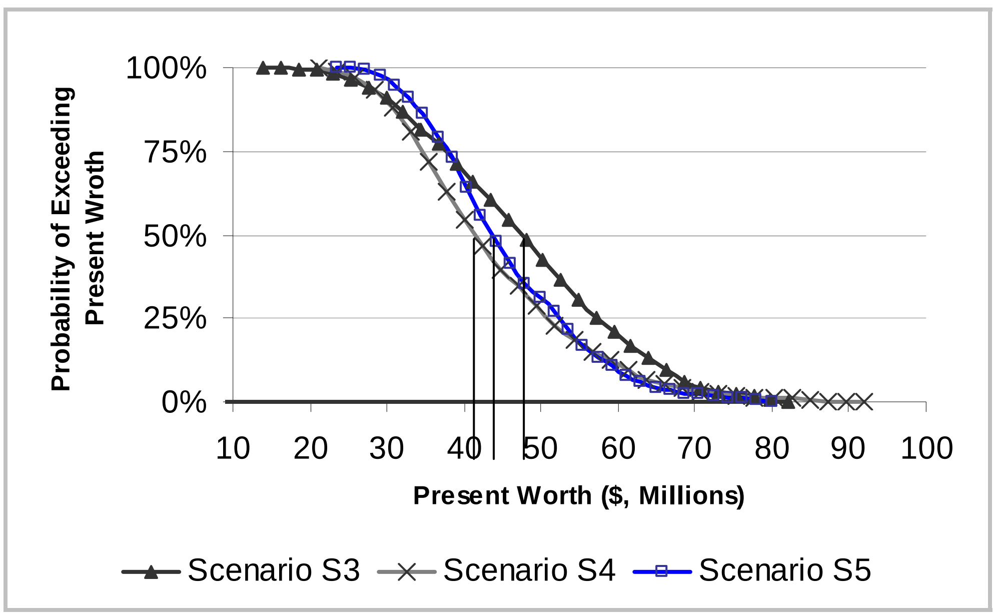

Figure 9.15: Risk Profile – Present Worth of Future Costs Vs Probability

The normal approximation results one-sided and two-sided *p*-value less than 0.0001 which is significant at 0.05 level. Therefore, there is statistically significant difference between the underlying distributions of PW of future costs under scenarios S4 and S5.

Mann-Whitney Two Sample Rank-Sum Test assesses the hypothesis that two independent samples of data have identical distributions. The results presented in Table 9.6 show that the Wilcoxson statistic equals 942216. The normal approximation results one-sided and two-sided *p*-value less than 0.0001 which is significant at 0.05 level. Therefore, there is statistically significant difference between the underlying distributions of PW of future costs under scenarios S4 and S5.

The Mann-Whitney Two Sample Rank-Sum Test compares entire distributions, and it is possible for two data samples to have significant Wilcoxson statistic but the same median – that is, two samples may have different distributions but approximately equal medians (Acock, 2008). The Median Test performs a *K*-sample test on equality of medians. To assess if the PW values under scenarios S4 and S5 are drawn from populations having the same median, a two-sample Median test is performed. The results presented in Table 9.7 show a $\chi^2(1)$ value of 13.448 with corresponding *p*-value of less than 0.001. This is significant as *p*-value is less than the significance level of 0.05. Therefore, the null hypothesis, that medians are equal, is rejected in favor of alternative hypothesis that they are not equal. Thus, the differences in present worth of future net costs are statistically significant.

Table 9.6: Two Sample Wilcoxon Rank-Sum (Mann-Whitney) Test Classified by Variable Scenario

Scenario	No. of Obs.	Sum of Scores	Expected Under Ho	Std. Dev. Under Ho	Mean Score
S4	1000	942216	1000500	12823.92	942.22
S5	1000	1058784	1000500	12823.92	1058.78
Statistics		942216			
Normal Approximation					
Z		-4.545			
One-Sided $\Pr < Z$		<.0001			
Two-Sided $\Pr > \lvert Z \rvert$		<.0001			

Table 9.7: Median Test

Greater Than Median	S4	S5	Total
No	541	459	1,000
Yes	459	541	1,000
Total	1,000	1,000	2,000
Pearson $\chi^2(1) = 13.448$, Pr < 0.001			

Figure 9.16 shows the change in present value of future cost (for scenario S5) when the discount rate deviates from the assumed base/average rate of 6%. For example, if the discount rate is 50% below the assumed rate of 6% - that is, 3% - the present value of future costs will be close to $61M over the 50 year planning horizon.

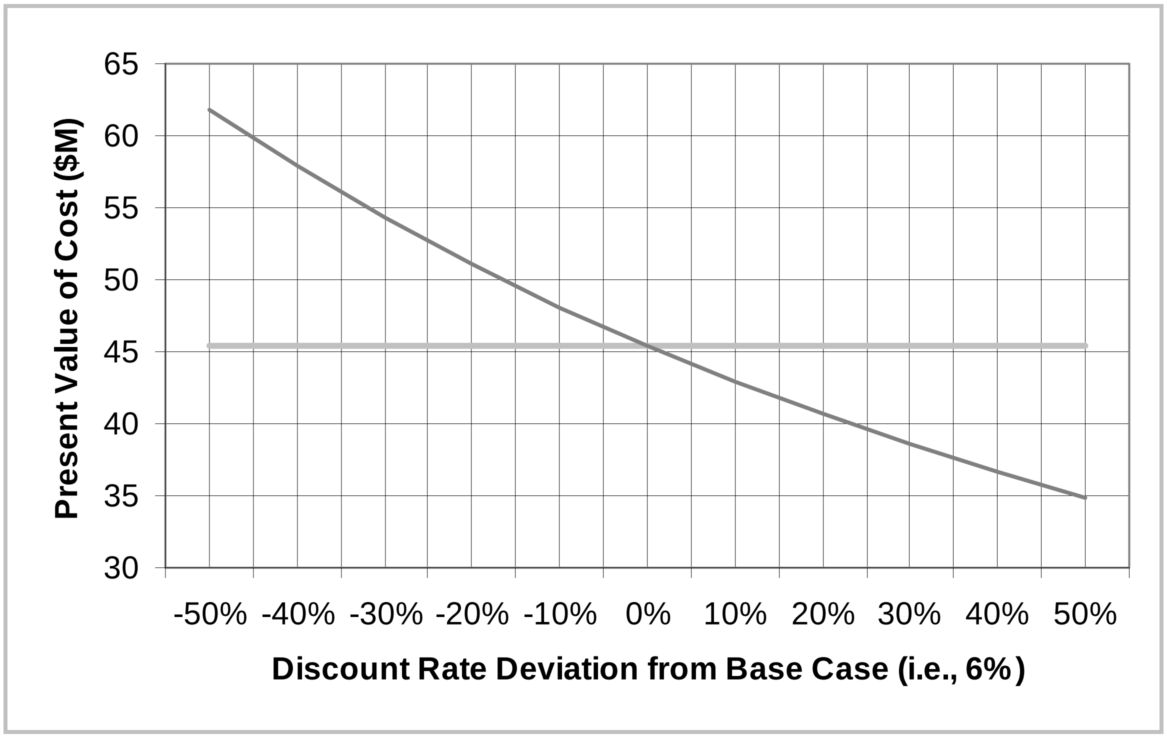

Figure 9.16: Sensitivity Analysis for Scenario S5 – Change in Present Value of Costs with Discount Rate

9.9 Discussion and Conclusions

This paper, second in the two part series, presented application of the strategic financial planning framework detailed in Part 1. The deterioration modeling and economic analysis is employed as a management tool for long-term financial planning and proactive management, rehabilitation, and replacement of wastewater pipelines. The analyses show that deferred maintenance of wastewater infrastructure is not cost-effective in the long-term, and that an early intervention can save millions of dollars for governments and public works departments responsible for providing and managing wastewater collection systems. The example case study used high quality condition assessment data from the City of Niagara Falls wastewater collection pipelines. Reinforced concrete pipes with diameter ranging from 250 mm to 750 mm – making up approximately 35% of the system – are considered. The analyses revealed that scenario S2 – that is, keeping the system at the current level of service – is the most expensive option with an estimated present worth of future costs ranging from $64.4M to $125.8M over the 50 year planning horizon. Scenario S4 – that is, replacing ICG 5 pipes and renovating ICG 4 pipes – is the most cost-effective alternative, and the estimated present worth of future costs for this option is $32.1M to $55.3M over the life-cycle analysis period of 50 years. Scenario S5, i.e., renovating ICG 3 and 4 pipes along with replacing ICG 5 pipes, is the least risky option having minimum uncertainty in terms of variability of present worth of costs. The estimated costs for this option vary between $35.4M and $55.3M over a 50 year period. Based on our analyses, we conclude that scenario S4 is the most cost-effective strategy, but assumes more risk as compared to scenario S5. Comparing scenario S5 (i.e., proactive maintenance, rehabilitation, and replacement) with scenario S2 (status-quo), the City can save up to $50M over the 50 year planning horizon.

The analysis presented in this paper supports the finding of Burgess (1990) provided that the least cost option is the only decision criteria and the risk dimension is ignored. The sustainable funding model proposed by Bainbridge and Macey (2005) did not take into account the risk resulting from the uncertainty associated with input variables. The methodology presented in NCHRP (2003) and Haas et al. (2006) for Life-Cycle Cost Analysis (LCCA) of transportation assets could be very laborious if large number of scenarios were involved. The deterioration model and LCCA presented in Haas et al. (2006) can be improved by using ordinal regression model and financial simulation. Tighe (2001) compared the life-cycle costs for pavements by fitting (*a*) normal, and (*b*) lognormal distributions to input and out variables. According to Limpert et al. (2001), the normal and lognormal distributions cannot be described in the *same* way – that is, using mean and standard deviation for both types of distributions. Salem et al. (2003) did not describe any model for output variable, and fell short of discussing the risk resulting from the variability in LCC (life-cycle costs) for alternative pavement management strategies. Variability in LCC for different alternatives should be taken into account because the least cost alternative – selected by ignoring the variability – may not be the least risky scenario. The risk-based LCC methodology for pavement infrastructure presented by Osman (2005) and FHWA (1998) is comparable to this study. However, Osman (2005) used internal rate-of-return as the decision metric, and both FHWA (1998) and Osman (2005) did not characterize the distribution of output variables.

Typically, output variable(s) from Monte Carlo distributions are characterized by their mean, μ, and standard deviation, σ, (see for e.g., Osman, 2005; Salem et al., 2003; Tighe, 2001 Greenberg, 2003). This practice assumes that the output variable is normal. This assumption needs to be verified before drawing conclusions. Furthermore, the risk due to variability of decision metric(s) is often overlooked which may result in selecting minimum cost but high risk alternative.

The framework and analyses presented in this series of papers provide a useful tool for strategic planning related to wastewater infrastructure management activities. The presented analyses and findings will improve decision-making concerning the development of long-term wastewater infrastructure management plans, commitment of resources, and establishment of defensible policies. It is recommended that the life-cycle cost studies be reviewed and revised (if necessary) at the end of every strategic planning cycle – may vary between 5 to 10 years depending upon a particular utility – due to changes in technology, operating environments, government legislations, business processes, and stakeholders' expectations. It is noted that the consideration of uncertainty and risk in economic analysis and financial planning is data intensive. Developing and maintaining a proper database system for inventory and condition assessment, and maintenance, renovation and replacement projects will provide the much needed data for future research in this area. At the minimum, such database should include the system attributes (e.g., pipe size, condition, rehabilitated/replaced length along with chainage, material, depth, original date of construction, rehabilitation/replacement date), site attributes (e.g., depth, location, traffic), and information about renovation/replacement techniques and related costs for each project. Collecting good quality data is the foundation for improved decision making related to the investment of billions of dollars in restoration and reconstruction of existing infrastructure, and will result in cost savings in the order of millions of dollars.

Acknowledgments

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Chapter 10
Conclusions, Contributions and Future Recommendations

10.1 General Summary

Wastewater collection networks continue to be the most neglected of all the civil infrastructure systems. The emphasis of this thesis was *what should be done* and *how to do it* for cost-effective and intelligent maintenance, rehabilitation and replacement of wastewater collection systems. Five research goals are established: (1) development of a high quality wastewater pipelines condition assessment database; (2) development of a framework to integrate heterogeneous data from various wastewater collection networks; (3) investigating the degradation behaviour of wastewater pipelines; (4) presenting a new strategic management framework; and (5) demonstrating the use of economic principles and deterioration model to support decision-making process. The conclusions from each of the above undertakings are discussed in detail at the end of each chapter. The following sections provide a summary of the limitations, and key findings and contributions of this research.

10.2 Conclusions and Contributions

10.2.1 Condition Assessment Database

Lack of good quality inventory and condition assessment data on wastewater collection networks is one of the limiting issues in understanding their performance behaviour. A high quality condition assessment database, WatBAMS (Waterloo Buried Asset Management Systems), using state-of-the-art Side Scanning and Evaluation Technology is developed. The development of WatBAMS not only provided the foundation for the research presented in this thesis but will support future research projects in this area that are not possible due to non-existent or incomplete datasets. WatBAMS integrates with the GIS (geographic information system) and can be easily upgraded to include operational and financial data. It contains key asset attributes, such as pipelines age, location, length, diameter, depth, and structural and operational condition, and can be easily mined to generate detailed reports on various types of defects and their severity along the length of a pipe.

10.2.2 Data Integration Framework

A standard data model for wastewater collection networks is highly unlikely as municipalities operate independent of each other, and define their business processes and data needs at local levels. This data needs to be aggregated by resolving data representational heterogeneity to create new knowledge. A data warehousing technique for wastewater infrastructure data integration is proposed. The example implementation – using XML technologies and specifications – suggests that it is a viable approach to aggregate data and information from a variety of municipal organizations. This will help in developing more powerful deterioration models and enhance our understanding about wastewater pipelines performance under a variety of operating conditions.

10.2.3 Deterioration Models

Two new deterioration models are proposed. The presented analyses are more vigorous and the proposed models are more parsimonious – have lesser number of parameters – than the existing deterioration models for wastewater pipelines. Parsimonious models tend to generalize because it is relatively easy to apply these models to untested situations. The importance of verifying model assumptions is also highlighted. The research found that the majority of existing models violate model assumptions and/or that assumptions were not verified due to data limitations. The deterioration of reinforced concrete (RC) pipes is found to be age related, owing to their susceptibility to corrosion due hydrogen sulphide, moisture, and other reactive agents in domestic sewage. For the City of Niagara Falls, it is estimated that, for RC pipes, the probability of being in the worst internal condition grade (WRc's ICG 5) surpassed the probabilities of being in lower grades at about 75 years of age. For vitrified clay (VC) pipes, it is concluded that they can have infinite life provided they are installed in good condition and are not subject to installation damage or excessive loadings. This infinite service life is greater than the current assumed life of 80 years. The proposed model(s) can be used to determine the wastewater pipelines service life, predict future condition states, and future rehabilitation and maintenance needs.

10.2.4 Framework for Multi-Perspective Management of Wastewater Collection Networks

New regulatory requirements demand more effective infrastructure management systems that are able to meet end-users expectations, protect public health and environment, and allow for efficient allocation of funds and greater disclosure. The research shows that the majority of asset management initiatives die down due to the gaps between strategy formulation and execution. A comprehensive review of management theories and tools is carried out. The review revealed that a multi-perspective strategic management framework based on modified balanced scorecard model will best meet the objectives of accountability, protecting public health and environment, and providing sustainable wastewater collection networks. The proposed framework takes into account four strategic perspectives – Social/Political, Financial, Operational/Technical, and Regulatory – and devises four strategic themes for sustainable wastewater collection systems. It should be noted that due to the enormity of the task, and time, space, and data limitations, only Operational/Technical perspective is discussed in detail with an example application using management tools, such as strategy maps and dashboard reports. The proposed framework and allied system helps in aligning asset management processes with an organization's mission and vision. By using the proposed framework, gaps between strategy formulation and implementation become obvious, and mitigating strategies can be formulated in real time.

10.2.5 Strategic Financial Planning

The work in strategic financial planning – that is, identification of short- and long-term funding needs and development of financial plans – at the wastewater collection network level is scarce. The proposed strategic financial planning framework takes into account the uncertainty of input variables to estimate short- and long-term financial requirements for effective maintenance, rehabilitation and replacement of wastewater collection systems. It also assists with devising capital improvement plans and answering critical questions, such as: (1) impact of alternative management strategies on the network condition over the planning horizon; (2) financial implications of various management alternatives; and (3) impact of discount rate on life-cycle costs. Research found that, for RC pipes at the City of

Niagara Falls wastewater collection network, rehabilitating ICG (internal condition grade) 4 pipes and replacing ICG 5 pipes is the most cost-effective strategy, whereas, rehabilitating ICG 3 and 4 pipes and replacing ICG 5 pipes is the least risky option. The analysis reveals that a proactive M,R&R strategy for RC pipelines can save up to $50 million for the City of Niagara Falls over the 50 year analysis period.

10.3 Considerations for the Research Implementation

The presented analyses and results are based on 400 Kms of wastewater pipelines' condition assessment data collected by the City of Niagara Falls. To develop deterioration models, utmost efforts were expended to ensure high quality, representative data for reinforced concrete (RC) and vitrified clay (VC) pipes from the City of Niagara Falls' wastewater collection system. As such, the presented deterioration models are applicable to the RC and VC wastewater pipelines at the City of Niagara Falls. It is recommended that these models be validated on data from other wastewater collection systems prior to their use.

The proposed models consider only the effects of pipes' *age* and *material* on the degradation behaviour of wastewater pipelines. It is to be noted that wastewater pipelines' deterioration is influenced by additional factors, such as workmanship during installation, soil type, soil corrosivity, ground conditions and disturbances, operating environment and load history, and pipelines' cleaning activities. It is the author's opinion that data required to quantify the impact of these factors is not readily available. For the City of Niagara Falls wastewater collection network, a review of geotechnical reports found that the ground water table was below the pipes' invert along with no significant difference in the soil backfill and pipe depth. Therefore, ground water table, depth of pipes' burial and soil backfill type were nearly constant across the City of Niagara Falls network and have no impact on pipes' deterioration.

The presented management framework proposed a mechanism to quantify the strategic management objectives with respect to the four perspectives: socio-political, operational/technical, financial, and regulatory. It is recommended that network owners update, standardize and implement the proposed performance indicators, as well as, the measurements' ratings and weights.

The wastewater pipelines' maintenance, rehabilitation and replacement (M,R&R) decisions are often site-specific and, therefore, depends – in addition to costs – on wastewater service providers' experience and availability of particular M,R&R technologies in the area. The case study to demonstrate the application of deterioration model and economic principles for long-term financial planning, considered average costs of intervention (from the published literature) for the M,R&R of wastewater pipelines in various internal condition grades during pipes' life-cycle. Furthermore, the condition of the RC wastewater pipes in the network was predicted using the deterioration model based on the condition assessment data from the City of Niagara Falls. It is recommended that a network specific analysis, similar to the one presented in this thesis, be completed to estimate long-term financial requirements for providing sustainable wastewater collection infrastructure.

10.4 Future Recommendations

To provide sustainable wastewater collection infrastructure, governments and regulators are emphasizing the importance of determining actual costs of service provision. The focus of physical infrastructure asset management is shifting towards service-oriented management where end-users are involved to define level of service and associated costs. Understanding the long-term performance of wastewater collection networks is very critical in this regards. The following recommendations are provided for the future work:

- High quality data needs to be collected and aggregated from various wastewater collection networks to generalize the deterioration behaviour of wastewater collection pipelines.

- Further research is required to validate the proposed deterioration model(s) in other networks and to model the deterioration of pipe materials other than RC and VC.

- A long-term pipelines condition assessment and performance monitoring initiative is highly desired.

- The proposed strategic model and related system needs to be implemented, and scoring system and weighting validated. An overall serviceability index, using a consensus building methodology, such as Delphi technique, will be useful.

- Historical cost and project data need to be compiled to ascertain materials, labour and construction costs over time. This is required to develop more reliable financial models, and will help in establishing a more useful and relevant construction cost index for buried utilities.