Graduate School Form 9
(Revised 6/03)

PURDUE UNIVERSITY
GRADUATE SCHOOL
Thesis Acceptance

This is to certify that the thesis prepared

By Hyeon-Shik Baik

Entitled "Development of an Asset Valuation Model for Wastewater Infrastructure Assets"

Complies with University regulations and meets the standards of the Graduate School for originality and quality

For the degree of Doctor of Philosophy

Signed by the final examining committee:

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Approved by: Head of the Graduate Program 12/10/03 Date

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Department Thesis Format Advisor

DEVELOPMENT OF
AN ASSET VALUATION MODEL
FOR WASTEWATER INFRASTRUCTURE ASSETS

A Thesis

Submitted to the Faculty

of

Purdue University

by

Hyeon-Shik Baik

In Partial Fulfillment of the

Requirements for the Degree

of

Doctor of Philosophy

December 2003

Dedicated to My Beloved Family

ACKNOWLEDGMENTS

First of all, I would like to express my sincere gratitude to my major advisor, Professor Dulcy M. Abraham, for her support and guidance throughout this research and during my entire stay at Purdue. Her critical mind inspired me to think every aspect of my work from different points of view. I will not forget her caring and friendliness. Thank you!

I also would like to express my gratitude to my committee members, Professor Daniel W. Halpin, Professor Kumares C. Sinha, and Professor Arnold L. Sweet, for sharing their precious time with me and allowing me to discuss the issues in my dissertation. They taught me not only the knowledge that I needed but also the attitude that a scholar should have.

I would like to acknowledge the assistance provided by Mr. Dean Gipson of the Metropolitan Wastewater Department of the City of San Diego. His assistance in providing data and providing insightful comments based on experience made this research possible.

This research was funded by the Purdue Research Foundation (PRF) and the National Science Foundation (NSF) Grant CMS-0201364. This support from Purdue University and the National Science Foundation is acknowledged and appreciated.

Many thank are due to Ms. Rachel Haas, Ms. Karen Studebaker, and Ms. Bonnie Sondgeroth in the CEM area and Mrs. Karen Hatke in JTRP for their assistance throughout my study at Purdue and the preparation of my dissertation.

Thank you also to my colleagues at Purdue, Dr. Boongyeol Ryoo, Dr. WonJae Lee, Seungki Park, Joohyung Lee, Seunghyun Chung, Jungwuk Kim, Sangwook Lee, Hyungseok Jeong, and Taehoon Hong, for your support and encouragement. The memories that I share with you will stay in my mind forever.

Special thanks to the Seoul Metropolitan Government. Without support from them, I would not have had the opportunity to start and finish my study at Purdue.

I would like to express my indebtedness to my parents, Kijun Baik and Sookhee Lee; my parents-in-law, Jung-Gil Kim and Sunsook Ahn; and my sisters for keeping me in their minds and hearts.

Last but not least, I would like to express gratitude to my wife, Booyong Kim, and my sons, Sean and Bryan. They are the reasons that I have come so far. Thank you for your understanding, patience, and support. I will return the caring and support that I received for the rest of my life. I love you!

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ABSTRACT

Baik, Hyeon-Shik, Ph.D., Purdue University, December, 2003. Development of an Asset Valuation Model for Wastewater Infrastructure Assets. Major Professor: Dulcy M. Abraham.

Valuation of infrastructure assets has drawn close attention in the U.S. since the Governmental Accounting Standards Board Statement 34 (GASB 34) was issued in 1999. GASB 34 recommends two valuation methods: the depreciation method and the modified approach. The depreciation method estimates the asset values by applying depreciation techniques to historical costs or replacement costs. When using the modified approach, the assets are not depreciated if they are maintained at or above the predefined minimum acceptance level using asset management systems. The expenditures on maintenance activities are recorded as expenses or capital in the annual financial reports of governmental agencies, depending on the maintenance activities and the valuation method employed. However, both methods do not adequately reflect the deterioration of infrastructure assets.

To account for the condition changes in infrastructure asset values, a valuation method incorporating the condition changes due to deterioration is presented in this study. The proposed valuation method estimates the asset value based on Markov chain-based deterioration models. The deterioration-based valuation value method can reflect the different levels of investments for maintenance and repair (M & R) activities and estimate the future asset values in a probabilistic manner by incorporating the different transition probabilities for different types of M & R activities, such as routine maintenance, preservation, and improvement. The comparisons of asset values obtained

from different valuation methods show substantial variations in asset values depending on the valuation method selected.

By incorporating the conditions of infrastructure assets, the deteriorated value method provides a more reasonable basis for governmental agencies for making decisions regarding future investments for M & R activities. The negative effects of delayed maintenance can also be captured in terms of reduced asset values.

The profitability of public agencies can be evaluated by estimating return-on-investment (ROI) using the values of infrastructure assets as investment and the profits generated from infrastructure assets as return. The deteriorated value method is also useful for the determination of infrastructure asset values for privatization by reflecting current or future condition of the infrastructure assets in their values.

CHAPTER 1. INTRODUCTION

1.1 Background

As an integral component of an asset management system, valuation of infrastructure assets allows public agencies to capture the worth of infrastructure assets and to demonstrate the accountability of the agencies to the general public. Infrastructure asset valuation also enables public agencies to maximize the value of infrastructure assets by effective and proactive management.

Infrastructure asset values can be used to show the financial soundness of public agencies. As discussed by Mansour-Moysey and Semmens (2001), return on investment (ROI) can be used to evaluate the profitability of public agencies by comparing the values of infrastructure assets to the profits generated from infrastructure assets. Profits are computed by subtracting expenses, including depreciation, from revenues collected through taxes and fees. The estimated ROI can be applied to the prioritization of maintenance activities for the allocation of limited resources. The ROI also can be used to justify changes in the pricing policies of utilities. When there is a need for an increase of taxes and fees for the use of services provided by infrastructure assets, the ROI of infrastructure assets can support the policy changes. For example, the three-year average ROI from 1996 to 1999 for earned revenue from the state highways of Arizona was –0.01 percent. The low ROI indicates that the value of the state highway is underestimated, and, accordingly, the public services are underpriced. The ROI of infrastructure assets, along with their valuations, allows infrastructure asset managers to allocate earned revenue to those assets that generate the revenue, supporting the use of funds generated from infrastructure assets for new construction and maintenance.

The need for asset valuation has received special attention since the Governmental Accounting Standards Board (GASB) issued Statement 34 (GASB 34):

Basic Financial Statements—and Management's Discussion and Analysis—for State and Local Governments in June 1999. GASB 34 recommends that governmental agencies adopt either the depreciation method or the "Modified Approach" for the valuation of infrastructure assets. According to GASB 34, when using the depreciation method for the valuation of infrastructure assets, the infrastructure asset values are historical costs less a depreciated amount and estimated salvage values. On the other hand, when using the modified approach, infrastructure assets are capitalized at historical costs and not required to be depreciated if the assets are (1) managed using an asset management system and (2) preserved at (or above) an established condition level. In such cases, the asset management system should have an up-to-date inventory, and condition assessments of the infrastructure must be performed on a regular basis in order to estimate the annual amount required to preserve the assets (GASB 1999). However, these two valuation methods do not accurately reflect the condition changes of infrastructure assets and generate other implications as described in the next section.

1.2 Problem Statement

Municipalities are recommended to report the values of wastewater infrastructure assets in their annual financial reports. The modified approach imposes more requirements on municipalities such as inventory update, condition assessment, and annual budget plan for preservation activities than the depreciation method. Thus, in many cases, municipalities prefer the use of the depreciation method for the valuation of wastewater infrastructure assets (Fickes 2002; GASB 2003).

The modified approach, however, provides advantages over the depreciation approach because the former approach reduces the uncertainties in infrastructure asset management. This is accomplished through the use of condition assessment, which predicts the future conditions of the assets, thereby enabling asset managers to formulate management strategies from a life-cycle perspective. The available resources can be allocated to more critical components of the assets. The cost for borrowing money could be lowered since the use of the modified approach enables the infrastructure asset managers to utilize infrastructure assets more effectively by employing inventory management and condition assessment techniques, which results in increased credibility when municipalities are financially rated.

Using the modified approach, the infrastructure assets are capitalized at historical cost or estimated historical cost, and the asset values will not change unless there are investments for improvements or additions to the existing infrastructure assets. There are other implications when the modified approach is used. Suppose that there are two different infrastructure assets in a city: Asset A and Asset B. They are similar in size and built at the same time and have the same initial construction cost. Asset A has been used extensively and frequent maintenance has been performed on it, whereas Asset B has not been used much and maintenance activities have been infrequent. After a few years in service, the condition of Asset A will be graded better than that of Asset B. If there are no major improvement activities performed and their conditions are above the established minimum acceptance level, the values of the two assets are the same according to the modified approach, even though the users and the asset managers consider Asset A to be more valuable.

Another implication arises due to the establishment of minimum acceptance levels. Suppose City A uses a condition rating system with grades ranging from 1 (best condition) to 5 (worst condition) for the wastewater infrastructure assets and establishes the grade of 3 out of 5 as the minimum acceptable condition level. City B also uses the same condition rating system and the acceptable condition level is set as 4. Naturally, City A has to make more investments on their infrastructure assets to maintain the assets at or above the established minimum acceptance level than City B does. However, since both cities meet the requirements recommended by GASB 34, i.e., they are both maintaining their infrastructure assets at or above the minimum acceptance level, they may receive the same rates when they are evaluated for the issuance of bonds. On the other hand, it is difficult for bond raters or auditors to quantify the differences in ratings for both cities in an objective manner during the evaluation processes.

The depreciation method expresses the loss in asset values in terms of depreciation. On the other hand, as the modified approach does not have a loss term in the financial report, infrastructure asset values do not decrease regardless of the condition changes but rather keep increasing as improvement and additions activities are performed until the time of disposal. Therefore, the depreciation method does not provide the approximate cost of asset ownership and the modified approach does not give any information regarding the cost of asset ownership (Harlow 2003).

As indicated by Maze (2000), one of the advantages of infrastructure asset valuation is the provision of information about conditions and performance of infrastructure assets using monetary terms rather than engineering terms. However, when the asset valuations do not reflect the deterioration of infrastructure assets in their values, the general public does not recognize the changes in the condition of the assets and the need for allocating funds for maintaining the asset values. To account for the condition changes in infrastructure asset values, a valuation method incorporating the changes in the asset condition due to deterioration is presented in this research. The deterioration-based valuation method provides asset values reflecting the loss of serviceability of infrastructure assets.

1.3 Framework of Research

The main objectives of this research are to develop a valuation model that reflects the condition changes of wastewater infrastructure assets and to investigate the impacts of different investment plans on the asset values. The framework of this research involves several major components as shown in Figure 1.1.

1. Review of methodologies and tools: Various methodologies for deterioration modeling, infrastructure asset valuation, and life cycle cost analysis are reviewed. Research tools such as regression analysis, nonlinear optimization, ordered probit model, rewards on Markov chain, and dynamic programming are examined to investigate the applicability of these tools.
2. Development of deterioration models: In order to determine the deterioration models for wastewater infrastructure assets, the Markov chain model is employed. The transition probabilities for the Markov chain are estimated based on two

approaches: the nonlinear optimization-based approach and the ordered probit model-based approach. The nonlinear optimization-based approach consists of regression analysis and nonlinear optimization, and the ordered probit model-based approach is composed of the ordered probit model and the incremental model.

3. Development of a deterioration-based valuation model: A valuation model reflecting the deterioration of wastewater infrastructure assets is developed based on the concept derived from the rewards on the Markov chain. The expected condition rating and the transition probabilities obtained from the deterioration model, in association with the transition cost matrices, are used for the estimation of the deteriorated values for different maintenance and repair (M & R) activities.
4. Life cycle cost analysis (LCCA): LCCA is performed to identify the optimal M & R alternatives for wastewater infrastructure assets. The dynamic programming technique is used for the optimization process, and the value iteration method is employed to find the optimal solutions.
5. Estimation of asset values: The developed deterioration-based valuation method is applied to estimate the infrastructure asset values when deterioration is considered and to analyze the variations of asset values when different valuation methods are used. The results of the LCCA are incorporated with the M & R strategies to investigate the impacts of different M & R investment plans on infrastructure asset values.

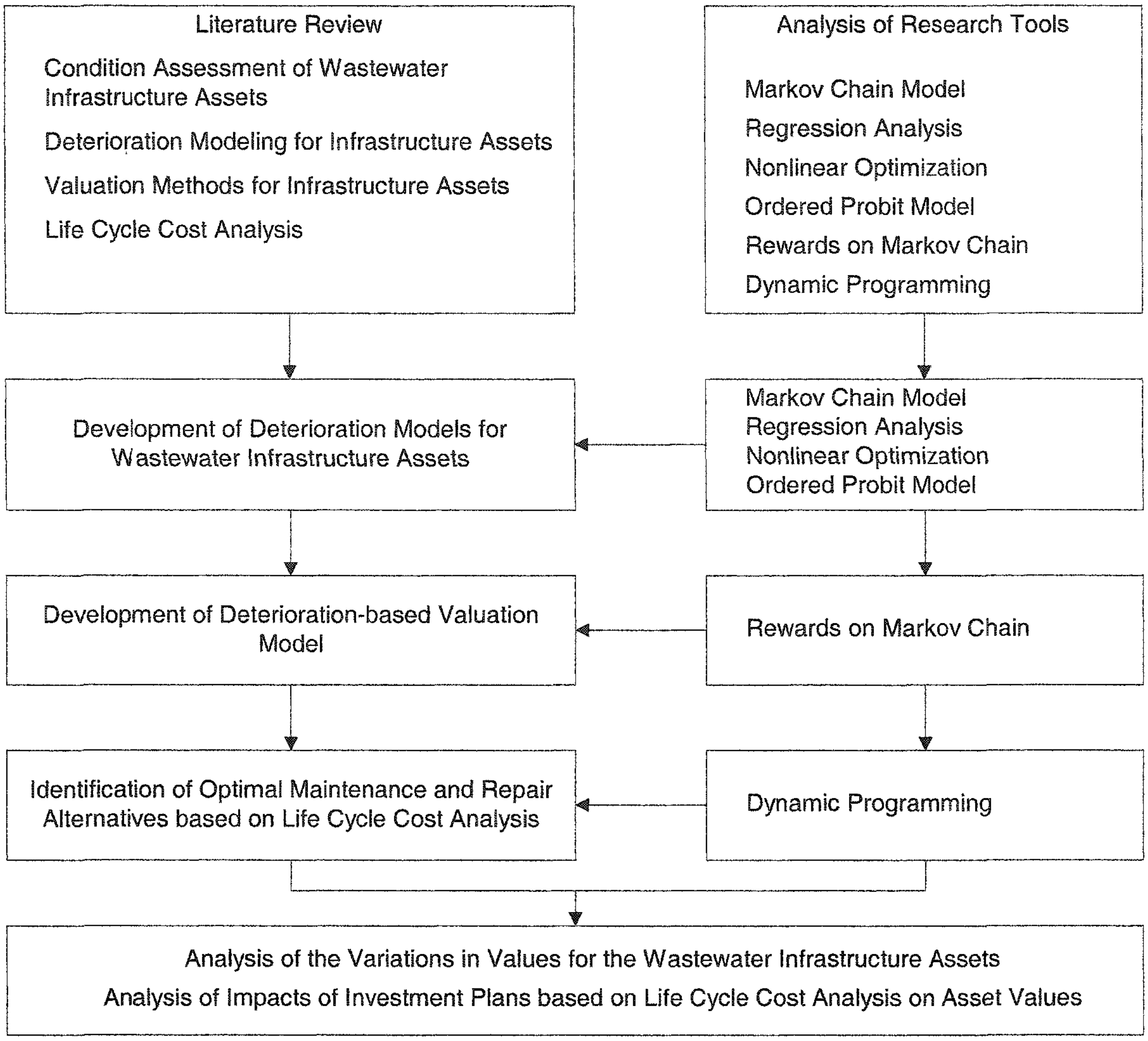


Figure 1.1: Research Framework

1.4 Dissertation Organization

This dissertation consists of six chapters. In Chapter 1, the background, problem statement, and scope of this research are presented. Chapter 2 provides a review of previous studies regarding the condition assessment of wastewater infrastructure assets, deterioration modeling, valuation methods for infrastructure assets, and life cycle cost analysis. In Chapter 3, methodologies for the development of deterioration models for wastewater infrastructure assets are described. A valuation model, based on the deterioration models, and its applications for three different M & R activities, i.e., maintenance, preservation, and improvement activities, are also presented in Chapter 3. Chapter 4 presents an overview of the dynamic programming optimization technique and its application to find the optimal M & R alternatives for wastewater infrastructure assets. Discussion of the transition probabilities and the detailed procedure for the estimation of deteriorated values when preservation and improvement activities are applied are also presented in Chapter 4. Chapter 5 contains the validation of the methodologies described in Chapters 3 and 4 by using the data for the wastewater infrastructure assets of the City of San Diego. The asset values estimated using different valuation methods for different M & R investment plans are also provided with the related discussions. Finally, Chapter 6 discusses the summary, contributions, and limitations of this research and recommends several issues as the future research topics.

CHAPTER 2. PRIOR RESEARCH IN INFRASTRUCTURE ASSET MANAGEMENT

Prior research studies in the area of infrastructure asset management are discussed in this chapter including of infrastructure asset management, condition assessment of wastewater infrastructure assets, deterioration modeling, valuation, and the life cycle cost analysis (LCCA) of infrastructure assets. Definitions and components of infrastructure asset management are initially addressed, followed by a discussion of condition assessment and different types of condition rating systems employed by municipalities. The methodologies used for deterioration modeling of infrastructure assets and techniques for estimating transition probabilities for a Markov chain-based deterioration model are then described. The chapter concludes with a summary of different valuation methods that can be used for infrastructure assets as well as a presentation of concepts, procedures, and applications of LCCA to infrastructure assets.

2.1 Infrastructure Asset Management

Managers of infrastructure systems face challenges daily in the operation and maintenance of infrastructure due to the demands of population growth and stricter regulations that require more rigorous control of infrastructure systems. Although infrastructure systems continue to age, resulting in the loss of serviceability, the funding level to maintain infrastructure systems does not increase at required levels. According to the American Society of Civil Engineers (ASCE 2003), the condition grade of wastewater infrastructure assets in the U.S. has declined from C in 1988 to D in 2002, and it is expected to decline even further in 2003. It was also projected that investments of at least $12 billion are required annually in addition to the current spending on wastewater infrastructure assets for the replacement of deteriorated facilities. As indicated by the EPA (2002), existing wastewater infrastructure assets receive a small portion of municipal budgets for condition improvement of assets compared to new construction. Therefore, to effectively deliver public services that rely on infrastructure systems effectively, a systematic management system is required.

Asset management is one of the most widely used terms for the management of infrastructure systems. As with infrastructure management, asset management strives to provide infrastructure systems services efficiently and cost-effectively. Since infrastructure systems were recognized as assets with monetary value in the late 1980s and early 1990s, asset management applies corporate business principles in the management system, including financial and management accounting methods (Cowe Falls et al. 2001).

Many organizations in the U.S. are developing concepts and frameworks for asset management of infrastructure assets, including the American Association of State Highway & Transportation Officials (AASHTO), the American Public Works Association (APWA), the American Society of Civil Engineers & Civil Engineering Research Foundation (ASCE & CERF), the Federal Highway Administration (FHWA), and the National Cooperative Highway Research Program (NCHRP). However, there is no widely acceptable definition for asset management (Cowe Falls et al. 2001). Some organizations define infrastructure asset management as strategies, whereas others regard it as processes for better management of infrastructure assets. The Association of Metropolitan Sewerage Agencies (AMSA 2001) defines asset management for wastewater utilities as "an integrative optimization process that enables a utility to determine how to minimize the total life-cycle cost of owning and operating infrastructure assets while continuously delivering the service levels that customers desire." The Transportation Association of Canada (TAC) defines infrastructure asset management as "a comprehensive business strategy employing people, information, and technology to allocate available funds effectively and efficiently among valid and competing asset needs (TAC 1999)." More definitions of asset management can be found in other literature (EPA 2002, FHWA-AASHTO 1997, RTA 1996, TNZ 2000).

Infrastructure asset management consists of various components and procedures, depending on the strategies and scopes of organizations. For example, FHWA (1999) recommends that an asset management system include strategic goals, inventory of assets, valuation of assets, quantitative condition and performance measures, alternative evaluation and program optimization, short- and long-term project selection plans, implementation, and feedback. According to the AMSA (2001), asset management involves five activities: strategy, asset retention, tool integration, business process redesign, and outreach and reporting. On the other hand, the EPA (2002) approaches asset management as a system to enhance the functionality and performance of infrastructure assets. Some of the key elements of asset management are the level of service definition, asset identification and valuation, failure impact evaluation and risk management, condition assessment, maintenance analysis and planning, and financial management (EPA 2002). Even though the approaches for infrastructure asset management are different among organizations, asset valuation is one of the common components. As indicated by Cow Falls et al. (2001), one of the objectives of infrastructure asset management is to determine the infrastructure asset values and minimize the loss in value through effective management.

2.2 Condition Assessment of Wastewater Infrastructure Assets

Condition assessment of infrastructure assets is important to gauge the current condition of the assets, and to predict future conditions. As prediction results are used for planning future inspection, maintenance and repair (M & R) scheduling, and M & R investments, condition assessment is one of the most important components of infrastructure asset management. Inspection and condition rating are the two major activities of a condition assessment.

2.2.1 Inspection and Data Acquisition

The first step in a condition assessment is the investigation of the current status of the structural and hydraulic condition of the assets. An assessment of the structural conditions of sewer pipes establishes the severity of the defects that are used for the deterioration modeling for prediction of future condition changes. The adequacy of the capacity of the existing wastewater infrastructure assets is evaluated through the assessment for hydraulic conditions. The structural conditions are investigated through internal inspections, whereas the hydraulic conditions are analyzed through hydraulic modeling. Infiltration/inflow are also investigated to identify the causes for structural failures and hydraulic surcharges.

Three methods are commonly employed for internal inspection, i.e., physical inspection, photographic inspection, and Closed Circuit TV (CCTV) inspection (EPA 1991). Physical inspection involves direct man-entry inspection of relatively larger sewers. Photographic inspection employs a camera to take a series of photos inside the sewer lines. CCTV inspection, which is currently the primary internal inspection method, uses a camera mounted on a casing pulled through the sewer with cables or a remotely controlled vehicle. The internal condition of the sewer pipes is shown through the TV monitor and recorded in a videotape. An example of the data collection form used for the assessment of sewer systems is shown in Table 2.1.

Table 2.1: Asset inventory data collection form (AMSA 2001)

Asset Inventory Data Collection Form – Wastewater Gravity Pipelines

Prepared By: **Date:**
System:
Location:
Soil Type/Conditions:
Type of Inspection: Visual ☐ CCTV ☐
Upstream Manhole:

Description:
Identification:
Diameter:
Depth:
Material of Construction:
Installation Date:

Condition Assessment:
Rating: 1 = Very Good; 5 = Very Poor

Steps:	1	2	3	4	5
Cover:	1	2	3	4	5
Barrel – Cracking:	1	2	3	4	5
Barrel – Corrosion:	1	2	3	4	5
Invert – Erosion:	1	2	3	4	5
Invert – Displacement:	1	2	3	4	5

Cost Information:
Original Cost: $ Replacement Cost: $
Operating Cost: $ /year Maintenance Cost: $ /year
Rehabilitation Costs & Frequency: $ ________ every ________ months
Estimated Remaining Useful Life:
___ 0 – 5 Years ___ 5 – 10 Years ___10 – 20 Years ____Other, indicate _____Years
Comments:

Pipeline Description:
Identification:
Upstream Manhole:
Downstream Manhole:
Diameter:
Material of Construction:
Installation Date:

Condition Assessment:
Rating: 1 = Very Good; 5 = Very Poor

Cracking:	1	2	3	4	5
Joint Displacement:	1	2	3	4	5
Corrosion:	1	2	3	4	5
Invert Erosion:	1	2	3	4	5
Debris/Blockage:	1	2	3	4	5
Root Penetration:	1	2	3	4	5

Utilization:
Mission Critical: Yes ☐ No ☐

Capacity Assessment:
☐ Undersized, Can't Meet Current Needs
☐ Meets Current Needs
☐ Oversized, Can Meet Future Needs

Cost Information:
Original Cost: $ Replacement Cost: $
Operating Cost: $ /year Maintenance Cost: $ /year
Rehabilitation Costs & Frequency: $ ________ every ________ months
Estimated Remaining Useful Life:
___ 0 – 5 Years ___ 5 – 10 Years ___10 – 20 Years ____Other, indicate _____Years
Comments:

2.2.2 Condition Rating Systems

Different types of condition rating systems are proposed and adopted by municipalities. In the following sections, key condition rating systems for wastewater infrastructure assets are presented.

2.2.2.1 Condition Rating System of the Sewerage Rehabilitation Manual (SRM)

In the rating system by the SRM (WRc plc 1994), the conditions of sewer pipes are rated based on the structural conditions of the pipes. The rating system consists of five grades considering the severity of fracture and deformation. The grades obtained from the assessment of the inside of the pipes based on structural conditions are then modified using supplementary information such as soil type and frequency of surcharge. The SRM condition grades and rating system for brick and concrete sewer pipes are shown in Tables 2.2 and 2.3.

Table 2.2: SRM condition grades for sewers (WRc plc 1994)

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 risk in short term but potential for further deterioration
1	Acceptable structural condition

Table 2.3: SRM condition rating system for sewers (WRc plc 1994)

Condition grade	Typical defect descriptions	
	Brick sewers	Clayware and concrete sewers
5	Already collapsed Missing invert Deformation > 10% and fractured Displaced/hanging brickwork and deformation < 10% Extensive areas of missing brickwork	Already collapsed Deformation > 10% and broken Extensive areas of fabric missing Fracture with deformation > 10%
4	Total mortar loss with deformation > 10% Deformation up to 10% and fractured Displaced/hanging brickwork Small number of missing bricks Dropped invert Moderate loss of level Spalling large Wear large	Broken Deformation up to 10% and broken Fracture with deformation 5 – 10% Multiple fracture Serious loss of level Spalling large Wear large
3	Total mortar loss without other defects Single bricks displaced Deformation < 5%, no fracture and only moderate mortar loss Spalling medium Wear medium	Fracture with deformation < 5% Longitudinal cracking or multiple cracking Minor loss of level More severe joint defects, i.e. open joint (large) or joint displaced (large) Spalling medium Wear medium
2	Minor cracking Surface mortar loss Spalling slight Wear slight	Circumferential crack Moderate joint defects, i.e. open joint (medium) or joint displaced (medium) Spalling slight Wear slight
1	No structural defects	No structural defects

2.2.2.2 Condition Rating System of WEF-ASCE

According to the Water Environment Federation and the American Society of Civil Engineers (WEF-ASCE 1994), the condition of wastewater infrastructure assets can be assessed by inspecting the Infiltration/Inflow (I/I) condition, the structural condition, and the hydraulics conditions. Infiltration is water that flows into the existing sewer pipes through defective pipes, pipe joints, lateral connections, or manhole walls. Infiltration occurs due to a high ground water level, storm events, or leaking water mains. Inflow is extraneous storm water that flows into the sanitary sewer system through roof leaders, cleanouts, foundation drains, sump pumps, and cellar, yard, and area drains. Infiltration causes the soil around the pipes to be washed into the pipe, which induces the failure of pipelines. Inflow increases the surcharging to sewer pipes, contributing to the deterioration pace of the sewer pipes. Insufficient hydraulic capacity can accelerate the deterioration of pipes due to exfiltration, which is the flow of sewage outside of the pipes through defects such as damaged joints and holes. The defects considered for the assessment of the structural condition of brick sewer pipe and for concrete and clay sewer pipe are described in Table 2.4.

Table 2.4: WEF-ASCE structural defects for sewer (WEF-ASCE 1994)

Brick sewer	Concrete and clay sewer
Sags Vertical deflection and cracks Missing bricks Lateral deflections Root intrusion Missing mortar Loose bricks Protruding lateral Soft mortar Depth of cover	Collapsed pipe Structural cracking with deflection (Longitudinal, Circumferential, Multiple) Slab-out Sag Structural cracking without deflection Cracked joints Open joints Holes Root intrusion Protruding joint material Corrosion (stage 1, 2, and 3) Pulled joint Protruding lateral Vertical displacement Depth of cover

In Table 2.4 the criticality of the defects is indicated by the order in which they are listed in the table. For example, for concrete and clay sewer pipes, the condition of collapsed pipes is more critical than pipes with cracks and deflection. Sewer pipes are rated for each defect using condition rating factors ranging from rating 2 to 5, where rating 2 is for a minimal collapse risk and rating 5 is for a collapse or collapse imminent case. External factors, such as soil type, surcharge, water table and fluctuation, and traffic, can be considerations for the rating of the given sewer pipelines.

2.2.2.3 Condition Rating System of the City of San Jose

The City of San Jose developed a condition assessment system for wastewater infrastructure assets based on three items, i.e., corrosion condition, structural condition, and impact factors (Fick et al. 1993). For the assessment, CCTV was used for the inspection of randomly selected pipes, and then the pipes were rated based on the severity of the condition. Corrosion conditions were grouped as light, medium, severe, or soil exposed. Structural conditions were rated depending on the level of defects such as cracks, fractures, breaks, deformities, collapses, holes, roots, infiltration, debris, alignment, and open and offset joints. The scores acquired from both inspected conditions were modified using impact factors. An impact factor was determined by considering the potential impact of the failure. The factors used to decide the impact factor were the pipe's location (industrial, residential, or commercial), traffic environment, and size. The total score of the pipes, which was used for the final condition rating, was obtained by multiplying the impact factor by the sum of the condition scores.

2.2.2.4 Condition Rating System of the City of Indianapolis

The City of Indianapolis performed a condition assessment for combined sewer pipes 60-inch (1,500 mm) or larger in diameter in 1995 (Greeley and Hansen 1996). Sewer pipes were inspected by walk-through inspections and pan-and-tilt TV inspections were used for pipes with high flows. Brick and segmented tile sewers were rated based on defects such as cracking, deflection, missing bricks, and dropped invert, and defects such as cracking, deflection, corrosion, and subsidence were used to rate both reinforced and cast-in-place concrete pipes.

Using the condition rating matrix in Table 2.5, the City of Indianapolis graded the condition of sewer pipes through a three-step evaluation. First, structural condition scores ranging from zero to three were used. A score of zero was assigned to pipes with no visible signs of deterioration and a score of three was assigned to pipes with high evidence of deterioration. The scores for each sewer pipe segment were then summed up to determine the condition rating based on a scale ranging from one to five, where one was good and five was severe. In the third and final step, the sewer condition ratings were modified using the internal (signs of infiltration, evidence of surcharge) and external (soil types, groundwater level, depth of cover) factors that were found during the inspection.

Table 2.5: Condition rating system of the City of Indianapolis (Greeley and Hansen 1996)

If the segment received the following combination of structural condition scores:			Which is a structural condition total of	Then the sewer condition rating was set at: (5 is the worst)
Number of 3's	Number of 2's	Number of 1's		
0	0	1	1	1
0	0	2	2	1
0	0	3	3	1
0	0	4	4	2
0	1	x	at least 2	3
0	2	x	at least 4	4
1	0	x	at least 3	4
1	1	0	5	4
1	1	at least 1	at least 6	5
0	3	x	at least 6	5
2	x	x	at least 6	5
3	x	x	at least 9	5

x = any number of structural condition scores
structural condition scores: 3 = excessive, 2 = moderate, 1 = minor deterioration
condition rating: 1 = "good", 2 = "fair", 3 = "moderate", 4 = "poor", 5 = "severe"

2.3 Deterioration Modeling of Infrastructure Assets

Deterioration models are developed based on the results of a condition assessment. These models allow the infrastructure asset managers to evaluate current conditions and to predict future conditions. Deterioration models also assist public agencies to plan future inspection schedules and to optimize investments for the renewal and rehabilitation of existing infrastructure assets.

As indicated by Ramawamy and Ben-Akiva (1990), an accurate deterioration model is important for the prediction of future conditions of infrastructure assets. To achieve this goal, various approaches have been used for the development of deterioration models for infrastructure assets to provide asset managers with accurate deterioration models since the concept of serviceability-performance was introduced by Carey and Irick (1960).

Deterioration models for infrastructure assets can be grouped into three classes according to the basis used for their development: empirical model, mechanistic-empirical model, and subjective-experience based model (Haas 2001). An empirical model typically uses regression analysis to identify the relationship between deterioration and pavement age based on measured or estimated variables such as deflection and accumulated traffic loads. A mechanistic-empirical model describes the deterioration using regression analysis based on calculated responses such as subgrade strain and pavement layer stresses as well as measured variables. Subjective-experience based models include Markov chain models and Bayesian models, which use condition data subjectively rated by inspectors for model development.

The techniques used for deterioration models have evolved from simple straight-line extrapolation and regression models to the more sophisticated probability-based stochastic models and artificial intelligence models. Based on the techniques and methods used, deterioration models for infrastructure assets can be categorized into three groups: deterministic models, stochastic models, and artificial intelligence models as shown in Table 2.6.

Table 2.6: Deterioration models for bridge infrastructure assets (Morcous et al. (2002))

Category	Technique	Method
Deterministic models	Straight-line extrapolation	-
	Regression models	Stepwise regression Linear regression Nonlinear regression
	Curve fitting models	B-spline approximation Constrained least squares
Stochastic models	Simulation models	-
	Markovian models	Percentage prediction Expected-value method Poisson distribution Negative-binomial method Ordered-probit model Random-effects model Latent Markov-decision process
Artificial intelligence models	Artificial neural networks	-
	Case-based reasoning	-

Deterministic methods were used for the prediction of the deterioration of infrastructure assets, particularly for pavement systems in the early 1980s. Even though these methods are relatively simple to use, the application of these methods for the development of deterioration models is limited because these methods do not consider the inherent stochastic property of infrastructure deterioration (Butt et al. 1987, Jiang and Sinha 1989, Scherer and Glagola 1994, Madanat and Wan Hashim 1995, Madanat et al. 1995, Bulusu and Sinha 1997). Artificial intelligence models include artificial neural networks (ANN) and case-based reasoning (CBR), and are applied for the prediction of the conditions of bridge systems (Sobanjo 1997, Tokdemir et al. 2000, Morcous et al. 2002). However, these methods also have limitations. Since ANN is an automated process of fitting a polynomial curve to the data sets, this method does not reflect the probabilistic behavior of deterioration (Morcous et al. 2002). The CBR method used for bridge systems looks for a bridge that has similar physical features, environmental and operational conditions, and inspection and maintenance history in a database. The deterioration pattern of the bridge detected from the database is used for the prediction of future deterioration for the bridge systems under consideration (Morcous et al. 2002). The limitation of this method is that it requires an extensive amount of data. To use this method, the ages of the bridges stored in the database should be longer than the sum of the age of the query case, i.e., the bridge whose deterioration is to be predicted, and the prediction period. The age of the query case is needed to search for similar bridge systems and the prediction period is needed to provide information about the future deterioration.

2.3.1 Nonlinear Optimization-Based Approach for Infrastructure Deterioration Models

Since the Markov decision process gained impetus in theory in the late 1950s and early 1960s, it had been applied extensively to the development of operational maintenance policies in various areas (White 1985, White 1989). In the area of infrastructure asset management, the Markov decision process was first used for the development of a deterioration model for the State of Arizona Pavement Management

System (Golabi et al. 1982). Since then it has been extensively used for infrastructure deterioration models (Madanat et al. 1995, Morcous et al. 2002).

One of the critical processes in the development of a Markov chain-based deterioration model is the estimation of transition probabilities. Among the techniques proposed for the estimation of transition probabilities, the nonlinear optimization-based approach has been widely applied for different infrastructure assets. This method employs nonlinear optimization technique to minimize the absolute distance between the condition data points (or average condition ratings from a regression curve) and the expected value obtained from the Markov chain model. Using an optimization process, transition probabilities expressed in matrix form can be estimated. In Table 2.7, the methods used for the estimation of the transition probabilities of Markov chain-based deterioration models are summarized.

Table 2.7: Deterioration models using the nonlinear optimization-based approach

Research group	Application	Method for estimating the transition matrix
Butt et al. (1987) Carnahan et al. (1987)	Pavement	one probability estimated per row nonlinear optimization $Min\ \sum \mid Y(t) - E(t,p) \mid$ Y(t): actual condition ratings E(t,p): expected condition value at age t
Jiang et al. (1988) Jiang and Sinha (1989)	Bridge decks	one probability estimated per row nonlinear optimization $Min\ \sum \mid Y(t) - E(t,p) \mid$ $Y(t)$: average condition ratings from regression (3rd order polynomial) $E(t,p)$: expected condition value at age t
Cesare et al. (1992)	Bridge decks	one probability estimated per row nonlinear optimization $Min\ \sum\sum (f_{i,n} - q_0 T^n)_i^2 C(n)$ $Min\ \sum \left[f_{i,n} - (q_0 T^n)_i \right]^2 C(n)$ $f_{i,n}$: relative frequency in state i at age n q_0: initial distribution T: transition matrix $C(n)$: number of bridges of age n

Butt et al. (1987) and Carnahan et al. (1987) developed a deterioration model for pavement systems using the nonlinear optimization-based approach for the Markov chain process. In this method, the Pavement Condition Index (PCI) was used to identify the condition ratings of the pavement systems. The PCI, which ranges from 0 to 100, with

100 being excellent condition, was converted into 10 condition states where state 1 (PCI of 90 to 100) was the best condition rating. The condition ratings measured from field inspection were used for a nonlinear optimization process to estimate the transition probabilities of the Markov chain model. By assuming that the pavement condition would not drop by more than one state in a single year, only one transition probability per each row of 10 x 10 (the number of condition states) transition matrix was estimated from the optimization process. Through this process, the probabilities that a pavement condition would stay at the same level after one transition were estimated using the optimization technique. Then, the transition probabilities that a pavement condition would drop to the next lower level could be calculated by subtracting the estimated probabilities from one. To account for the changes in traffic loads and maintenance policies over time, ideally one transition matrix was required to have a different transition matrix for each year. However, due to the lack of data availability, a zoning system was employed in the estimation of transition probabilities. A zone represented a six-year period and it was assumed that each zone had a constant rate of deterioration. Thus, the Markov chain was assumed to be homogeneous in a zone and the transition probabilities in a zone were taken to be constant.

For bridge systems, several studies employed the nonlinear optimization-based approach for the development of deterioration models. Jiang et al. (1988) and Jiang and Sinha (1989) applied the nonlinear optimization-based approach for bridge systems in the State of Indiana. One point that should be noted in these cases is that, for the estimation of transition probabilities using nonlinear optimization, average condition ratings were used in lieu of actual condition rating data. The average condition ratings were obtained from a polynomial regression curve fitted to the condition rating data.

The nonlinear optimization-based approach was also used for the development of deterioration models for bridges in the State of New York (Cesare et al. 1992). The transition probabilities of the Markov chain model were estimated based on the minimization of the summation of the squared difference between the relative frequency and the expected value from the Markov chain model. Each result was weighted by the number of bridges for each age of bridges. Another method presented in the study was the minimization of the mean-square error for each row of transition matrix.

2.3.2 Econometric Model-Based Approaches for Infrastructure Deterioration Models

The nonlinear optimization-based approach has been employed to provide information for the prediction of future performance of infrastructure assets by using nonlinear optimization techniques. However, this method has been criticized for its limitations. According to Madanat et al. (1995), the nonlinear optimization-based approach does not reflect the structure of the deterioration process resulting in the failure of explicit modeling of condition changes. This lack of structure prevents the representation of the inherent nonstationary nature of deterioration. For this reason, a zoning technique was introduced and the transition probabilities in a zone were assumed to be constant. Madanat et al. (1995) also pointed out that the linear regression model used in the nonlinear optimization-based approach is not appropriate since the dependent variable, in this case the condition ratings, is discrete and ordinal. The assumptions of zero error mean and a constant variable are not satisfied and the ordinal scale of the independent variable is not reflected when using the regression model.

Ben-Akiva and Ramaswamy (1993) introduced the concept of the latent nature of infrastructure deterioration. Deterioration is not directly measurable. Only indicators of deterioration can be measured using the measurement techniques. The condition ratings, which form the basis for determining the condition status of infrastructure assets, are based on the observable indicators of deterioration. For the prediction of true infrastructure deterioration, the relationship between the deterioration and the indicators should be explained.

Extensive efforts have led to the development of deterioration models for infrastructure assets using econometric models, application of which are shown in Table 2.8.

Table 2.8: Econometric model-based deterioration models

Research group	Application	Method for transition matrix
Ramaswamy and Ben-Akiva (1990)	Pavement	Simultaneous equation model
Ben-Akiva et al. (1991)	Pavement	Latent variable model
Ben-Akiva et al. (1993)	Pavement	Latent variable model
Ben-Akiva and Ramaswamy (1993)	Pavement	Latent variable model
Ben-Akiva and Gopinath (1995)	Pavement	Latent variable model
Madanat and Wan Ibrahim (1995)	Bridge decks	Poisson regression model and Negative binomial model
Madanat et al. (1995)	Bridge decks	Ordered probit model
Madanat et al. (1997)	Bridge decks	Random-effects binary probit model
Bulusu and Sinha (1997)	Bridge decks	Random-effects binary probit model
Prozzi and Madanat (2000)	Pavement	Duration model
Mauch and Madanat (2001)	Bridge decks	Duration model
Mishalani and Madanat (2002)	Bridge decks	Duration model
Lee and Chang (2003)	Bridge expansion joints	Ordered probit model

2.3.2.1 Simultaneous Equation Model

Ramaswamy and Ben-Akiva (1990) developed a simultaneous equation deterioration model for highway pavement. This model incorporated the effects of maintenance activities by considering them exogenously in the deterioration model. In this study, the maintenance activities are defined as an endogenous variable that is affected by pavement condition, traffic, and other explanatory variables. The simultaneous equation used for the pavement deterioration model consists of two equations. One equation describes the relationship between condition, maintenance, and other explanatory variables affecting deterioration, and other equation represents the extent of maintenance performed by using conditions and other explanatory variables.

2.3.2.2 Latent Variable Model

The latent variable model, which was used for the development of deterioration for pavements, starts from the recognition of performance (or deterioration) of infrastructure assets being unobservable (Ben-Akiva et al. 1991, Ben-Akiva et al. 1993, Ben-Akiva and Ramaswamy 1993, Ben-Akiva and Gopinath 1995). Since the data collected during field inspections are only indicators of deterioration, models are needed to explain the relationship between unobservable deterioration and the explanatory variables such as age, traffic, and maintenance activities, and the relationship between deterioration and the indicators of the deterioration, i.e., extent of damage. The structural model can explain the relationship between unobservable deterioration and the explanatory variables. The measurement model can describe the relationship between deterioration and the indicators of the deterioration. The latent variable model simultaneously estimates the parameters of the two models for the development of deterioration models.

2.3.2.3 Poisson and negative binomial model

Madanat and Wan Ibrahim (1995) employed the Poisson regression model and the negative binomial regression model for developing a bridge deterioration model. The Poisson regression model estimates the probability of the occurrence of discrete outcomes based on a Poisson distribution. The negative binomial model is used when the variance of data is greater than the mean. As indicated by Washington et al. (2003), it is a common mistake to model count data as continuous data using regression analysis. This mis-modeling can result in negative or non-integer prediction values that are inconsistent with count data. When using the Poisson model, the deterioration of infrastructure assets and explanatory variables can be explicitly related. There is no need for grouping data based on the characteristics of infrastructure assets. This allows the use of an entire data set in the Poisson model, which can produce a full transition matrix for the Markov chain model. The Poisson model also reflects the discrete nature of condition rating data.

One property of the Poisson model is that the variance of the random variable is equal to the mean. This can be a shortcoming of the Poisson model for modeling real world activities where the variance of actual data is often significantly greater than the mean. In this case, a negative binomial model can be used for deterioration modeling. The drawbacks of these two models are that they cannot account for the ordinal nature of condition data.

2.3.2.4 Ordered Probit Model

The ordered probit model is another application of econometric models for infrastructure deterioration modeling and can be used for the modeling of discrete outcome data (Washington et al. 2003). Among the discrete outcome models, the probit model assumes the disturbance term to be normally distributed. A disturbance term in a probit model supports the possibility that (1) significant variables can be omitted from the model due to lack of data availability, (2) the functional form of the model may not be correct, (3) proxy variables may be used, and (4) the variations of parameters for explanatory variables may vary across observations. Madanat et al. (1995) used the ordered probit model for bridge deterioration models to account for the drawbacks of the expected value method, which is called the nonlinear optimization-based approach in this research and is described in Section 2.2.2. The researchers developed a model, named "incremental models," for deterioration modeling. An incremental model estimates the probabilities that can be used for the prediction of condition changes for transitions from previous conditions. Madanat et al. (1997) and Bulusu and Sinha (1997) developed a binary probit model for bridge deterioration using panel data. The effects of previous deterioration to future deterioration were accounted for by the random effects model, which randomly draws some cross-sectional units from large populations for the analysis. The presence of heterogeneity of panel data was therefore explained by this model. Another application of the ordered probit model can be found in the study conducted by Lee and Chang (2003) for bridge deck expansion joints. In this study, the probabilities that different types expansion joints stay in a condition state at different ages are estimated using the ordered probit model for the bridges in the State of Indiana.

2.3.2.5 Duration Model

Duration models account for the elapsed time between the occurrence of events or the duration of an event in a statistical manner. Even though duration data, which are typically continuous, can be modeled using least square regression, the duration models can provide some other insights as described hereafter.

Prozzi and Madanat (2000) developed a duration model for pavement failure. This model can estimate the probabilities that a pavement section will experience a failure given that no failure has occurred by a given time based on hazard function using Weibull distribution. If the probabilities that the pavement segment will not fail after a given time is of interest, the survival function can be used to obtain the probabilities. Mauch and Madanat (2001) employed the Cox proportional hazard model to predict the probability distribution of the time that bridge decks will take to stay in a condition state. From the reverse perspective, using this method, the probability distribution of times between the condition changes can be predicted. This method is different from the state-based model, which is a common method for infrastructure deterioration models using the Markov chain model, in a sense the state-based model provides the probability distribution that a facility will experience condition changes at a given time. Mauch and Madanat (2001) indicated that if condition data are observed over a short period of time or are measured infrequently, the state-based model is more appropriate for the development of deterioration models. Mishalani and Madanat (2002) also used the duration model to find the probability distribution of time that bridge decks take to stay in a state or to change condition states. The study also presented the procedures to estimate transition probabilities from the duration models by determining the probability that a facility experiences a condition change during a certain period of time.

2.3.3 Deterioration Models for Wastewater Infrastructure Assets

The maintenance activities of municipalities have focused primarily on pavement and bridge systems that exist on the ground and are easily visible, whereas wastewater infrastructure assets are located underground and are managed on a crisis-basis. This situation causes reactive rather than proactive maintenance and the perpetuation of the lack of data, which then results in greater. To reduce the uncertainties in predicting future condition changes, various deterioration models were developed for wastewater infrastructure assets.

In Germany, a cohort survival model was applied to wastewater infrastructure assets (Mehle et al. 2001). In this model, sewer systems were grouped based on the construction period and other features such as material, size, and soil conditions. Each group of classification was regarded as a cohort. Using the Herz distribution, survival and transition probabilities could be estimated. Wirahadikusumah et al. (2001) adopted the nonlinear optimization-based approach, which was used for pavements and bridges, for the deterioration modeling of large combined sewers. An exponential distribution was employed for the regression analysis. The average condition ratings obtained from the exponential distribution was used for the nonlinear optimization to estimate the transition probabilities of the Markov chain model. A duration model was employed by Kleiner (2001) for the estimation of the amount of time it takes large infrastructure assets, including trunk sewers, to stay in a condition state. The Weibull probability distribution was used for survivor function, and due to insufficient data, Monte Carlo simulation was performed to generate data for the calculation of the durations in states. Micevski et al. (2002) presented a Markov chain-based deterioration model for storm water pipes in Australia. The transition probabilities were estimated using the Metropolis-Hastings algorithm.

2.4 Valuation of Infrastructure Assets

Since there is no market for trading infrastructure assets, various techniques are proposed as the valuation methods for infrastructure assets, which includes historical cost, book value, replacement cost, written-down replacement cost, equivalent present worth in place, productivity realized value, market value, salvage value, and option value as shown in Table 2.9 (Lemer 1998; Cowe Falls and Haas 2001; Snelgrove and Haas 2001; Amekudzi et al. 2002).

The historical cost method determines the infrastructure asset values from the accumulated costs for facilities, including initial construction cost and subsequent M & R costs. The book value method estimates the infrastructure asset value by subtracting the depreciation obtained from the straight-line method, the declining balance method, and the sum-of-years-digits method from the historical cost. The replacement cost method computes the asset values based on the estimated cost required for the replacement of the existing infrastructure assets at the time of valuation. The written-down replacement cost method uses the replacement cost adjusted for deterioration of infrastructure assets for valuation. The equivalent present worth in-place method estimates the infrastructure asset values by considering inflation, depreciation, and wear and tear of the assets using historical costs. The market value can be determined between the buyer and the owner of infrastructure assets when they agree to trade the assets. The salvage value is the remaining value at the end of the useful life of infrastructure assets, which is the estimation of obtainable value from disposing of or recycling the assets.

Among the described valuation methods, the book value method is recommended by the Governmental Accounting Standards Board (GASB) as one of the valuation methods for infrastructure assets. In the report published by the Transportation Association of Canada (Cowe Falls and Haas 2001), the applicability of valuation models for different infrastructure assets, such as pavement, bridges, signs, building, etc. is presented.

Table 2.9: Valuation methods for infrastructure assets

(Lemer (1998); Cowe Falls and Haas (2001); Snelgrove and Haas (2001); Amekudzi et al. (2002); Herabat et al. (2002))

Valuation methods	Description	Features
Historical cost	Procurement and subsequent related costs	Provides investments in time series so that the investments among the assets can be compared at specific times. Inflation and deterioration are not considered.
Book value	Accumulated historical cost less all allowable depreciation	Three traditional depreciation methods (straight-line method, declining balance method, and sum-of-years-digits method) can be applied. Inflation is not considered. Can mislead the values of older assets since a large amount is deducted for depreciation.
Replacement cost	Current cost of replacing the asset	Potentially provides inflated value. Does not account for the preservation history.
Written down replacement cost	Uses current market prices to determine costs to rebuild/replace an asset in its current condition	Considers deterioration. Accounts for the preservation history.
Equivalent present worth in place	Historical costs adjusted for inflation, depreciation, and wear and tear	Useful for comparing rates of return with other investments. Requires a number of assumptions for inflation, depreciation, and wear and tear.
Productivity realized value	Present worth of future benefits for the remaining service life of the facility	Useful for assets generating revenues. Requires assumptions for the estimation of future benefits and remaining service life.
Market value	Price that a buyer is willing to pay and an owner is willing to accept for the transfer of the asset	Applicable to public agency disposal or sale of assets. Conjectural until offer is actually received.
Salvage value	Present worth of the amount obtainable from disposing or recycling facility	Used for other valuation methods.

2.4.1 Valuation Methods for Pavements and Bridge Assets

In addition to the aforementioned valuation methods, several approaches have been developed and applied to the valuation process of infrastructure assets such as pavement systems and bridge systems. Maze (2000) presented an example for the estimation of values for highways and local roads using the perpetual inventory method, whereby the value of infrastructure assets is the summation of the capital investment in the current year and the value of the infrastructure assets of previous year less depreciation. The depreciation is computed from the previous year's value multiplied by an annual depreciation rate (Fraumeni 1999). Kadlec and McNeil (2001) presented a case for the valuation of the pavement system of the City of Hopkins, Minnesota based on the book value method using the straight-line depreciation method. Mansour-Moysey and Semmens (2001) estimated the value of Arizona's state highway system using an accounting concept of subtracting expenditures on maintenance, administration, law enforcement, bond interest, tax collection cost, and depreciation from revenues generated from collected taxes and fees and federal aid for the highway system.

The New Zealand National Asset Management Steering Group (N.Z. NAMS 2001) presented the optimized depreciated replacement cost method for the valuation of infrastructure assets using the concept of replacement cost and depreciation. In this case, the replacement costs were optimized by reducing the over-designed and redundant elements of the assets. Herabat et al. (2002 and 2003) used a cost approach for the valuation of the pavement systems of Thailand by subtracting the accrued depreciation from replacement cost. In this study, the accrued depreciation consisted of physical deterioration, functional obsolescence, and external obsolescence. Physical deterioration can be estimated based on the maintenance costs required to upgrade the pavement system to the minimum acceptable condition level. Functional obsolescence can be determined from the additional costs for the modification of an element of the pavement system according to the new regulations or design standards, whereas expenditures for the repair of highways due to flood damages are used as the external obsolescence. According to Johnson (2003), the California Department of Transportation (CalTrans) uses a written-down replacement cost approach for the valuation of its bridge systems.

Bridge asset values are estimated based on the replacement costs obtained from contract bid documents, which are adjusted to the current condition using the bridge health index.

2.4.2 Past-Based and Future-Based Approaches

As suggested by Amekudzi et al. (2002), valuation methods can be classified into past-based and future-based approaches according to the time frame for the asset valuation. Past-based approaches, such as historical cost, book value, and equivalent present worth in-place, require historical cost or expenditure data for the determination of infrastructure asset values. In the case of wastewater infrastructure assets, as indicated by Malik et al. (1997), Black & Veatch (1999), and Wirahadikusumah et al. (2001), neither condition data nor historical cost data are well documented. Thus, past-based valuation methods are not likely to be used as a valuation method. Even if the historical cost data were available, review and retrieval of the cost data for construction, maintenance, and improvement activities from the paper documents is very labor intensive. For that reason, CalTrans excluded the historical cost method for the valuation of its approximately 12,700 bridges (Johnson 2003). As an alternative, GASB 34 provides an example for the estimation of infrastructure asset value based on the book value, using the deflated replacement cost as the historical cost (GASB 1999). Future-based approaches, such as productivity-realized value, market value, and salvage value, are only useful when full or partial information about revenues or income that can be generated from the operation of infrastructure assets is available. Since this information is not generally available in the area of wastewater infrastructure assets, municipalities are not likely to employ future-based valuation approaches.

Only the written-down replacement cost method and the equivalent present worth in-place method consider the deterioration of infrastructure assets in their valuation. Since other methods, such as book value and market value, are rooted in accounting-based frameworks, these methods do not directly reflect the value of maintenance activities.

2.5 Life Cycle Cost Analysis

Life cycle cost analysis (LCCA) allows governmental agencies to consider all possible costs throughout the useful life of infrastructure assets in the selection of the best alternative to minimize the total cost required for construction, operation, and maintenance. Since LCCA pursues proactive M & R activities that prevent the failure of infrastructure assets, it can save costs incurred after failure, such as emergency contractor fees, staff overtime, and unplanned repairs (EPA 2002). In this section, an overview of LCCA is presented, including concepts, techniques, procedures, and applications of LCCA.

2.5.1 Concepts of LCCA

Life cycle cost analysis (LCCA) can be defined as "a process for evaluating the total economic worth of a usable project segment by analyzing initial costs and discounted future cost, such as maintenance, user, reconstruction, rehabilitation, restoring, and resurfacing costs, over the life of the project segment" (TEA-21 1998). Through LCCA the effectiveness of investment alternatives can be evaluated over a certain period of time and the most cost-effective alternatives can be selected (Hall et al. 2003).

Even though LCCA has been used to identify the most cost-effective alternative for infrastructure projects, many governmental agencies are hesitant to adopt LCCA due to the limited availability of crucial data and the limited understanding of the concepts and techniques of LCCA (FHWA 1999). According to a survey conducted by Arditi and Messiha (1999), 60% of the responding municipalities did not use LCCA. However, LCCA provides valuable benefits over arbitrary planning of future investments in addition to the provision of the most cost-effective investment alternative. LCCA enables governmental agencies to have a platform on which to justify the decisions made on the expenditure of funds collected from taxpayers. Documentation associated with the LCCA process can demonstrate the systematic approach to the management of infrastructure assets. The documents produced during the LCCA process can be a good source for future decisions and for the education of new employees (FHWA 2002).

The components of LCCA include the analysis period, the discount rate, the agency costs, the user costs, the salvage value, and the computation techniques (Hall et al. 2003). The analysis period is the time horizon over which the LCCA is performed. According to FHWA (2002), the analysis period should be long enough to include at least one rehabilitation activity for each alternative after the initial construction. For example, an analysis period of at least 35 years was recommended for all pavement projects by FHWA (1996). In Canada, 20- to 30-year analysis periods are used for pavements (TAC 1997).

The discount rate is considered in LCCA to reflect the changes in the value of money by taking the interest rate and inflation into account. This rate is used for the computation of the present value of the initial and future costs so that the total cost required for each alternative can be compared in constant dollars. The U.S. Office of Management and Budget (OMB) recommends the use of discount rates that consider both the interest rate and inflation in order to conduct a cost-effectiveness analysis as shown in Table 2.10 (OMB 2003). The discount rates for analysis periods not listed in Table 2.10 can be obtained by using the linear interpolation, and analysis periods longer than 30 years can use the 30-year discount rate.

Table 2.10: Discount rates for LCCA (OMB 2003)

Analysis Period	Discount Rate
3 years	1.6
5 years	1.9
7 years	2.2
10 years	2.5
30 years	3.2

The agency costs are the estimated expenditures for initial design and construction, operation, and subsequent M & R activities. The user costs are the costs that can be incurred by users during the use of the infrastructure assets, which can be estimated for two different situations, such as in-service user costs and work zone user costs. The in-service user costs are the costs incurred during the normal use of infrastructure assets, while the work zone user costs are the extra costs incurred during the construction and M & R activities. For pavement systems, the user costs can consist of three cost components, such as vehicle operation costs, delays costs, and accidents costs.

The salvage value is the residual value at the end of the analysis period. The Arizona Department of Transportation (1991) estimated the salvage value as a percent of the initial costs by using a function based on the probability of rebuilding highway at the end of the analysis period, the initial cost, the rehabilitation cost, the thickness of the original pavement and overlays, the worth of the recycled materials, and the removal cost. FHWA (1998) recommends the salvage value to be proportional to the cost invested for the last rehabilitation activity during the analysis period. The proportion for this case can be calculated from the remaining useful life of the last rehabilitation activity at the end of the analysis period divided by the expected useful life of the rehabilitation activity. The techniques for LCCA are presented in the next section.

2.5.2 Techniques for LCCA

Techniques used for LCCA can be categorized into two groups: (1) the techniques for selection of optimal M & R alternatives, and (2) the techniques for economic analysis. Techniques for the selection of optimal M & R alternatives determine when and what types of activities should be applied for maintenance and repair. Optimization techniques, such as linear programming, integer programming, and dynamic programming, can be used to provide an optimal M & R alternative at a minimum cost.

Techniques for economic analysis include the net present value (NPV), the equivalent uniform annual costs (EUAC), the rate of return (ROR), the benefit-cost (B/C) ratios, and the break-even analysis (Tighe 2001). The NPV method finds the equivalent worth of all possible costs incurred during an analysis period to the present time. The EAUC is an equal annual series of costs for an analysis period, which can be derived from the NPV. In the ROR method, the RORs for the investments are compared to the maximum attractive rate of return (MARR) to determine the acceptability of an alternative. The MARR is a policy set up by the decision-makers of an agency. When the B/C ratio method is used, alternatives with ratios greater than or equal to one are accepted. However, the benefits of public projects are difficult to estimate. The break-even analysis method first finds a single factor that influences the selection of an optimal alternative between two competing projects. The break-even point can be found by equating the costs for both projects, and using it as a criterion for evaluating the acceptability of the alternatives (Sullivan et al. 2002).

FHWA (2002) recommends the use of the NPV method for LCCA. The EUAC method can be also used. However, the ROR method, the B/C ratio method, and the break-even analysis method are not used much for LCCA of infrastructure assets due to the difficulty of quantifying costs and benefits (Tighe 2001).

2.5.3 Procedures of LCCA

The procedures of LCCA are well described by FHWA (1998 and 2002) and include:

1. Establish design alternatives
2. Determine activity timing
3. Estimate costs (agency and user)
4. Compute life-cycle costs
5. Analyze the results

The first step involves the identification of initial design and subsequent M & R activities required for each alternative. These activities should include not only the initial construction and rehabilitation but also periodic maintenance activities. Based on the expected useful lives of the selected alternatives, the analysis period for LCCA can be determined in this step. The second step is related to the planning of schedules of the future M & R activities and the duration during which the M & R activities will occupy work zones. This provides the basis for the estimation of agency costs and user costs, and when these funds are needed. The schedules for M & R activities can be determined by a deterioration curve obtained from historical performance records. However, when these records are not available or applicable, engineering judgement can provide the information for decision-making. In the third step, pertinent costs are estimated. Even though the agency costs are of primary interest, it is desirable to include the user costs in LCCA. The discount rate is determined in this step to compare the total cost of each alternative in constant dollar terms. In the fourth step, life cycle costs are computed using economic analysis techniques to select the most cost-effective project. The last step entails review and modifications, if needed.

2.5.4 Applications of LCCA for Infrastructure Assets

As available funding is limited, the use of LCCA is promoted in the planning of future investments for maintenance, repair, and rehabilitation of existing infrastructure assets. In the area of pavement management, Carnahan et al. (1987) applied LCCA to find the most cost-effective maintenance solutions for pavement systems. Using the dynamic programming technique, maintenance activities were identified for different condition states at different times at the minimum costs for a 20-year planning horizon. Some of the types of maintenance activities included routine maintenance, overlay with different thickness, and reconstruction. The LCCA procedure based on dynamic programming was also applied to pavement systems by Feighan et al. (1988). In this study, different maintenance alternatives were evaluated over a 25-year planning horizon to determine the optimal maintenance policies. A prioritization scheme for the allocation of a limited budget was also presented in the study. The details of the prioritization scheme and the sensitivity analysis for investigation of the impacts of changes in input values for LCCA can by found in Feighan et al. (1989 a, b).

LCCA was applied to the selection of pavement types between hot-mix asphalt concrete (HMAC) and Portland cement concrete (PCC) in Olmsted and Waseca Counties in the State of Minnesota (Embacher and Snyder 2001). The EUAC method was used to estimate the annual cost for M & R activities. When sections with similar ages and traffic volumes were compared, PCC pavements were generally found to be more cost-effective than the HMAC pavements in both counties. However, when the entire sections were compared, the HMAC pavements were more cost-effective than the PCC pavements.

Labi and Sinha (2003) applied LCCA to the evaluation of the effectiveness of preventive maintenance for pavement systems. The NPV method was used for the computation of costs. The increase in area under the performance curve (or deterioration curve) due to maintenance was used for computing the benefits. The cost-effectiveness of maintenance strategies was evaluated by using an incremental benefit cost ratio method. The incremental benefit is the difference between the benefits obtained from any maintenance strategy and the base strategy. The incremental cost is the difference between the costs required for any strategy and the base strategy.

For bridge systems, Jiang (1990) used the dynamic programming and the integer programming techniques to select projects for rehabilitation and replacement by maximizing the effectiveness of M & R activities to an entire bridge system subject to budget constraints. The annual budget for maintenance is divided into several portions using dynamic programming, and specific projects in the portions are selected using integer programming.

Frangopol et al. (2001) recommend using the concept of reliability for the management of a bridge system. The reliability-based approach, in association with Monte Carlo simulation, provides the number of bridges requiring rehabilitation at a certain time in the future. The deterioration of bridges can be expressed using the reliability index, which represents the level of safety from failure, with corresponding probability distributions. Using the random numbers generated from Monte Carlo simulation based on the probability distribution obtained from reliability analysis, the expected number of bridges in certain reliability states at predetermined points in time can be computed.

Zayed et al. (2002) applied the dynamic programming technique for LCCA in the determination of optimal policy for the maintenance of steel bridge painting. Deterioration models are developed based on Markov Chain model for steel bridge painting, and then based on the transition probabilities obtained from the Markov Chain-based deterioration model, optimal alternatives are selected using the dynamic programming optimization technique.

In the area of wastewater infrastructure assets, LCCA using dynamic programming for the identification of optimal alternatives also has been applied to wastewater infrastructure assets (Abraham et al. 1998, Wirahadikusumah et al. 1999, Wirahadikusumah and Abraham 2003). In these studies, the framework of the approach was similar to the one used for pavement systems, however, the detailed inputs and assumptions required for the analysis reflected the characteristics specific to wastewater infrastructure assets.

CHAPTER 3. DEVELOPMENT OF A VALUATION MODEL FOR WASTEWATER INFRASTRUCTURE ASSETS

The valuation methods for infrastructure assets recommended by GASB 34 do not consider the impacts of condition changes. Therefore, a deterioration based valuation model is presented in this chapter. The following sections describe an overview of a Markov chain model and two approaches for the estimation of transition probabilities, the nonlinear optimization-based approach and the ordered probit model-based approach. A deterioration-based valuation model is then presented as well as comparisons of the infrastructure asset values using different valuation methods for three cases: 1) maintenance activities are performed, 2) preservation activities are performed, and 3) improvement activities are performed.

3.1 Markov Chain-Based Deterioration Models

Among the different models used for the development of deterioration models for infrastructure assets, the Markov chain model has been widely used for pavement systems (Butt et al. 1987), bridge systems (Jiang and Sinha 1989), and sewer systems (Wirahadikusumah et al. 2001). The deterioration model developed in this study was also based on the Markov chain model. The following sections describe the concept of a Markov chain model and the approaches used for the estimation of transition probabilities.

3.1.1 Markov Chain Model

A stochastic process is an approach to describe the characteristics of a system, such as condition states of infrastructure assets at time t using random variables. In the stochastic process, the value of the system characteristic at time t, X_t, is not known with certainty. Thus, X_t can be expressed as a random variable with probabilities. The Markov chain is a type of discrete-time stochastic process (Winston 1994). If a stochastic process has a Markov property, it is called a Markov chain. The Markovian property is that the conditional probability of any future event depends only on the present state and is independent of the past states (Ross 2000). The Markovian property can be expressed as equation (3.1) for all states $i_0, i_1, \ldots, i_{t-1}, i_t, i_{t+1}$ and all $t \geq 0$.

$$P(X_{t+1} = i_{t+1} \mid X_t = i_t, X_{t-1} = i_{t-1}, \ldots, X_1 = i_1, X_0 = i_0) = P(X_{t+1} = i_{t+1} \mid X_t = i_t) \tag{3.1}$$

In a Markov chain, the assumption that the probability does not change over time is called the *stationary assumption*. Thus, for all states i and j and all t, $P(X_{t+1}=j \mid X_t=i)$ is independent of t as expressed in equation (3.2).

$$P(X_{t+1} = j \mid X_t = i) = p_{ij} \tag{3.2}$$

where, p_{ij} = probability that given the system is in state i at time t, it will be in a state j at time $(t+1)$.

When the system moves from state i during one period to state j during the next period, it is said that a *transition* from i to j has occurred. The p_{ij}'s are often referred to as the *transition probabilities* for the Markov chain. The concept of transition for five states using transition probabilities is shown in Figure 3.1.

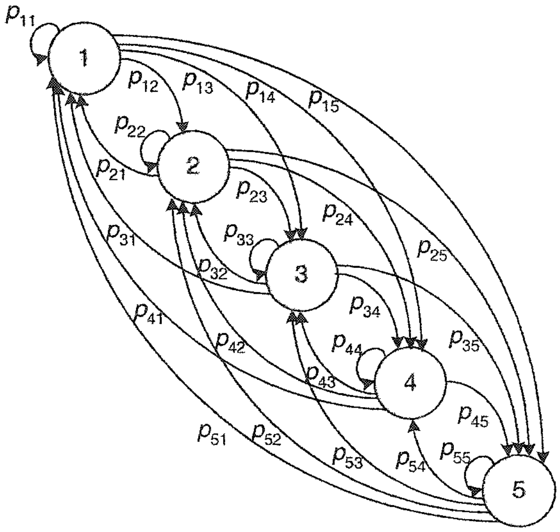


Figure 3.1: Markov chain model

In Figure 3.1, the arrows indicate the possible transitions in the system and p_{ij}'s denote the probabilities associated with the transitions. For instance, the state 1 has five possible transitions with probabilities p_{11}, p_{12}, p_{13}, p_{14}, and p_{15}. Similarly, the state 5 also has five possible transitions.

The transition probabilities are commonly expressed as an m x m matrix called the *transition probability matrix* (or *transition matrix*) ***P***. The transition probability matrix ***P*** and its characteristics are given in equation (3.3), (3.4), and (3.5).

$$P = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1m} \\ p_{21} & p_{22} & \cdots & p_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ p_{m1} & p_{m2} & \cdots & p_{mm} \end{bmatrix} \tag{3.3}$$

$$\sum_{j=1}^{m} P(X_{t+1} = j \mid P(X_t = i)) = 1 \tag{3.4}$$

$$\sum_{j=1}^{m} p_{ij} = 1 \ \text{ for } i = 1, 2, \ldots, m \tag{3.5}$$

The probability of the system moving from state i to state j after n periods (n transitions) is called *n-step transition probability*, $p_{ij}^{(n)}$. The one-step transition probability is $p_{ij}^{(1)}=p_{ij}$.

$$p_{ij}^{(n)} = P(X_{m=n} = j \mid X_m = i) = P(X_n = j \mid X_0 = i) \qquad (3.6)$$

Based on the Chapman-Kolmogorov equation, the n-step transition probability matrix, $\boldsymbol{P}^{(n)}$, can be obtained by multiplying the matrix $\boldsymbol{P}$ by itself n times (Ross 2000). Thus,

$$P^{(n)} = P^n \qquad (3.7)$$

Let the *initial state vector*, $\boldsymbol{Q}^{(0)}$, be the probability that the Markov chain is in state i at time 0. Then, the *state vector*, $\boldsymbol{Q}^{(n)}$, which is the probability that the chain is in state j after n transitions, can be expressed as shown in equation (3.8) (Winston 1994).

$$Q^{(n)} = Q^{(0)} P^{(n)} \qquad (3.8)$$

where, $Q^{(0)} = [q_1, q_2, \ldots, q_m]$

q_i = probability of being in state i at time 0

3.1.2 Estimation of Transition Probability

One of the critical procedures of the development of a Markov chain-based deterioration model is the estimation of transition probability. The two different approaches used in this study are described in the following sections.

3.1.2.1 Nonlinear Optimization-Based Approach

The nonlinear optimization-based approach used in this study for the estimation of transition probability consists of two stages: regression analysis and nonlinear optimization. Regression analyses were performed first, and then by minimizing the sum of absolute difference between the expected values from the regression model and the Markov chain model, the transition probabilities of the Markov chain model were estimated using nonlinear optimization techniques. This approach is based on previous research studies performed for pavements (Butt et al. 1987, Carnahan et al. 1987), bridges (Jiang et al. 1988, Jiang and Sinha 1989), and large combined sewers (Wirahadikusumah et al. 2001).

If condition assessment data and related property data are available for sewer pipes, the pipes can be grouped to evaluate the effects of factors such as pipe material, size, depth of installation, surrounding soil conditions, ground water level, etc., on the condition of sewer pipes. Then, the condition rating data and the ages of pipes can be fitted using regression analysis for each data group. The average condition rating at age t can be calculated from the regression equation. The nonlinear optimization technique is then applied to estimate the transition probability of a Markov chain model as shown in equation (3.9).

For better understand of the nonlinear optimization given in equation (3.9), the concept of "zoning" should be addressed. As indicated by Butt et al. (1987), the environment affecting the deterioration of infrastructure assets changes over time, resulting in the violation of the assumption of a constant transition period over the life of pavement. To resolve this problem, a "zoning" concept was introduced. whereby, the entire life of the infrastructure assets was divided into several periods that are defined as zones. In each zone, the transition period and the corresponding transition probability were assumed to be constant, producing a homogeneous Markov chain. The period for zoning is determined based on engineering judgement. One factor for this decision can be the inspection interval. For instance, a six-year period is common for a zone for pavements (Butt et al. 1987) and bridges (Jiang and Sinha 1989) whereas a 25-year period was used for large combined sewers (Wirahadikusumah et al. 2001).

$$Minimize \sum_{t=t_s}^{t_e} \sum_{n=1}^{N} | Y(t) - E(n,P) | \tag{3.9}$$

subject to: $0 \leq p_{ij} \leq 1, \quad i, j = 1, 2, \ldots, m$

where, m = number of states (condition ratings)

t = age of wastewater infrastructure assets

t_s = starting age for each zone

t_e = ending age for each zone

n = number of transition periods (stages)

N = total number of transition periods in each zone

$Y(t)$ = average condition rating at age t, estimated from regression function

$E(n, P)$ = expected value of condition ratings of wastewater infrastructure assets for n transitions estimated based on the Markov chain model

The expected condition rating, $E(n, P)$, can be obtained by multiplying the state vector of stage n as shown in equation (3.8) and the *condition rating vector*, $\boldsymbol{S}$. If the wastewater infrastructure assets are graded based on a five-level condition rating system ranging from 1 to 5 with condition 1 being the best, the condition rating vector, $\boldsymbol{S}$, can be represented as $\boldsymbol{S}$ = [1 2 3 4 5]. Then, the expected value, $E(n, P)$, can be calculated using equation (3.10).

$$E(n,P) = Q^{(n)}S^T = Q^{(0)}P^{(n)}S^T \tag{3.10}$$

where, $Q^{(n)}$ = condition vector at stage n

$Q^{(0)}$ = initial condition vector at stage 0

$P^{(n)}$ = probability matrix after n transitions

S^T = transpose of the condition rating vector $\boldsymbol{S}$.

In equation (3.10), the n-step transition probability matrix, $\boldsymbol{P}^{(n)}$, contains unknown probability values. These values are estimated using the nonlinear optimization technique given in equation (3.9) for each zone. For example, if a six-year period (N) is used for a zone, the optimization for the first zone starts with t_s = 1 and ends with t_e = 6. For the second zone, t_s will be 7 and t_e will be 12, and so on. If the average condition ratings calculated from the regression function are greater than the worst condition, which is 5 in the assumed case, the $Y(t)$ value in equation (3.9) remains the same afterwards regardless of the age. When using the nonlinear optimization-based approach, if the transition period (stage) is the same as the unit of age used in the analysis, the increment of t and n in equation (3.9) will be the same. However, if these periods are different, the increments for t and n should be different. For instance, if a five-year transition period is used in the modeling, the increments for stage n are equal to one, while the increments for age t should be five.

Once the transition probability for the first zone is estimated, the state vector, $Q^{(n)}$, can be calculated using equation (3.8). Assuming that a six-year period is used for a zone, and P_1 denotes the transition probability matrix for the first zone, the state vectors for each transition can be expressed as shown below:

Zone 1:

1st transition: $Q^{(1)} = Q^{(0)} \times P_1$
2nd transition: $Q^{(2)} = Q^{(1)} \times P_1 = Q^{(0)} \times P_1^2$
...
6th transition: $Q^{(6)} = Q^{(5)} \times P_1 = Q^{(0)} \times P_1^6$

Then, the state vector for the 6th transition, $Q^{(6)}$, obtained from the calculation above is used as the initial state vector for the second zone. Using the transition probability matrix for the second zone, P_2, the state vectors for the second zone are:

Zone 2:

1st transition (7th in total): $Q^{(7)} = Q^{(6)} \times P_2 = Q^{(0)} \times P_1^6 \times P_2$
2nd transition (8th in total): $Q^{(8)} = Q^{(7)} \times P_2 = Q^{(0)} \times P_1^6 \times P_2^2$
...
6th transition (12th in total): $Q^{(12)} = Q^{(11)} \times P_2 = Q^{(0)} \times P_1^6 \times P_2^6$

Using the same procedure, the state vectors for the remaining zones and hence the entire transition can be computed. Using the state vectors multiplied by the transpose of condition rating vector, S^T, as shown in equation (3.10), the expected condition ratings for each transition based on a Markov chain can be calculated. Plotting the expected condition ratings along with ages provides the deterioration curve for the prediction of future performance of wastewater infrastructure assets.

3.1.2.2 Ordered Probit Model-Based Approach

Various econometric models have been applied to develop deterioration models for infrastructure assets as addressed in Chapter 2. This trend partially stems from the characteristics of infrastructure deterioration and the condition ratings data collected from the field inspection. As argued by Ben-Akiva and Ramaswamy (1993), deterioration of infrastructure asset is unobservable directly. Instead, the indicators of infrastructure deterioration represented by damages or distress are measurable entities.

Econometric models can provide information regarding the unobservable variables (or latent variables) whereas the regression analysis used for the nonlinear optimization-based approach for a Markov chain cannot account for the relationship between the latent variables and indicator variables. The condition rating data of infrastructure assets are mostly discrete and ordinal. McKelvey and Zavoina (1975) indicated that linear regression violates the assumptions of zero error mean and constant variance for discrete data. Ordinary regression does not recognize the ordinal scale of a dependent variable (condition rating) since linear regression assumes that the difference between condition ratings 1 and 2 is the same as the difference between condition ratings 3 and 4 (Greene 2003).

For the analysis of ordered discrete outcomes, two probability models, i.e., the ordered probit model and the ordered logit model, have been used since the mid-1970s (Washington et al. 2003). The difference between these two models is the probabilistic distribution of the disturbance term. If the disturbance term is assumed to be normally distributed, the probit model is employed, whereas the logit model assumes the disturbance term to follow logistic distribution. In the area of the development of deterioration models for infrastructure assets, ordered probit model has been used.

Madanat et al. (1995) applied the ordered probit model for bridge decks, and Lee and Chang (2003) used the ordered probit model for bridge expansion joints.

In this current research, the concepts of an ordered probit model along with incremental models used for the deterioration modeling of bridge decks (Madanat et al. 1995) are applied for the estimation of transition probabilities for wastewater infrastructure assets. In the following sections, the concepts of incremental model and the theoretical background of the ordered probit model are presented.

3.1.2.2.1 Incremental Model

The concept of the incremental model was introduced by Madanat et al. (1995) to use the probabilities obtained from the ordered probit model for the development of a Markov chain-based deterioration model, in which the increments, i.e., the changes in condition ratings, during a transition period are calculated and used as the discrete outcomes in the ordered probit model. The probability estimated for a specific discrete outcome (increment) can be interpreted as the transition probability of the Markov chain model. If the condition of a sewer segment is moved from condition state i to j during a transition period, the increment for this transition is $(j - i)$. By estimating probabilities for increments for every condition state, the values of each row of the transition probability matrix can be obtained. Since the transition matrix is estimated for each transition, the transition matrix based on this approach is nonstationary, or time dependent, as opposed to the stationary transition matrix for each zone obtained from the nonlinear optimization-based approach for the Markov chain model.

3.1.2.2.2 Ordered Probit Model

In the ordered probit model, the unobserved (latent) variable, z_{ik}, is used as the basis for the ranking of discrete data. In this study, the actual deterioration of a wastewater infrastructure asset is the latent variable assumed to be continuous and varying between 0 and $+\infty$. Let k and i denote a specific sewer segment and its condition state, respectively. Then, the latent deterioration variable, z_{ik}, can be specified as a linear function as shown in equation (3.11) (Washington et al. 2003).

$$z_{ik} = \beta_i X_k + \varepsilon_{ik} \tag{3.11}$$

where, β_i = vector of estimable parameters for condition state i

X_k = vector of variables determining the discrete ordering for segment k

ε_{ik} = random disturbance term

Using measurement equations that map the continuous latent variable (deterioration), z_{ik}, to discrete indicator variable (condition increments), y_{ik}, the relationship between the latent variable and the indicator variable can be defined as shown in Figure 3.2, and equation (3.12) (Washington et al. 2003).

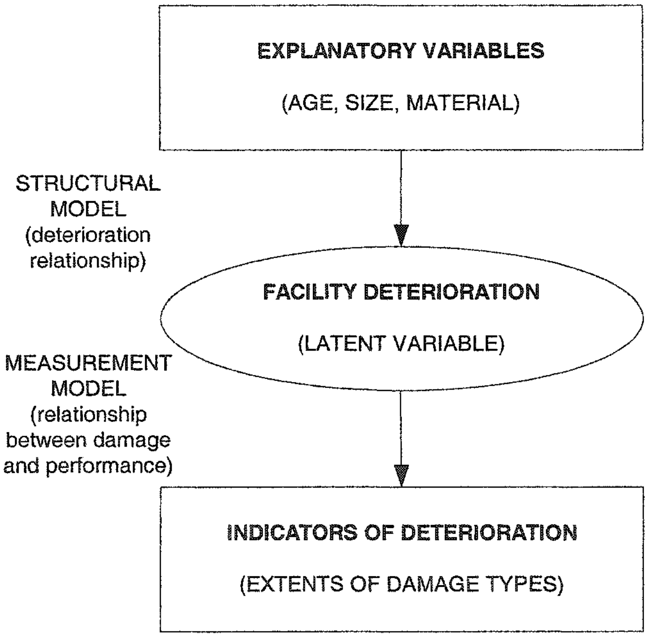


Figure 3.2: The latent variable model facility performance (Ben-Akiva and Ramaswamy 1993)

$$y_{ik} = j - i; \ if \ \ \mu_{i(j-i)} \le z_{ik} \le \mu_{i(j-i+1)}; \ \ for \ \ (j-i) = 0, \ldots, I-1 \tag{3.12}$$

where, (j-i) = change in condition state of segment k after one transition

μ = thresholds. $\mu_{i0} = 0$ and $\mu_{i(j-i+1)} = \infty$

I = highest number for condition rating

The equation (3.12) indicates that, if the latent deterioration, z_{ik}, falls between the two thresholds, the change of condition rating (increment) becomes y_{ik}. The increment data for wastewater infrastructure assets with condition ratings ranging from 1 to 5 can be expressed as shown in equation (3.13).

$$\begin{aligned} y_{ik} &= 0 \quad \text{if } z_{ik} \le \mu_{i1} \\ y_{ik} &= 1 \quad \text{if } \mu_{i1} \le z_{ik} \le \mu_{i2} \\ y_{ik} &= 2 \quad \text{if } \mu_{i2} \le z_{ik} \le \mu_{i3} \\ y_{ik} &= 3 \quad \text{if } \mu_{i3} \le z_{ik} \le \mu_{i4} \\ y_{ik} &= 4 \quad \text{if } \mu_{i4} \le z_{ik} \end{aligned} \tag{3.13}$$

By substituting equation (3.11) for equation (3.12), the ordered probit model can be expressed as equation (3.14).

$$y_{ik} = j - i; \text{ if } \mu_{i(j-i)} - \beta_i X_k \le \varepsilon_{ik} \le \mu_{i(j-i+1)} - \beta_i X_k; \text{ for } (j-i) = 0, \ldots, I-1 \tag{3.14}$$

For an ordered probit model, the disturbance term, ε_{ik}, is assumed to be normally distributed with mean = 0 and variance = 1. Therefore, the probability that the condition changes, y_{ik}, is equal to $(j\text{-}i)$ can be expressed using cumulative normal distribution, $\Phi(.)$, as shown in equation (3.15). This probability is the transition probability from condition i to j.

$$P(y_{ik} = j - i) = \Phi(\mu_{i(j-i+1)} - \beta_i X_k) - \Phi(\mu_{i(j-i)} - \beta_i X_k); \text{ for } (j-i) = 0, \ldots, I-1 \tag{3.15}$$

The likelihood function for the *maximum likelihood estimation* (MLE) over the population of K_i, which is the total number of sewer segments that are in state i, can be expressed as equation (3.16).

$$L(y \mid \beta, \mu) = \prod_{k=1}^{K_i} \prod_{(j-i)=0}^{I-1} \left[\Phi(\mu_{i(j-i+1)} - \beta_i X_k) - \Phi(\mu_{i(j-i)} - \beta_i X_k) \right]^{\delta_{ik}} \tag{3.16}$$

where, $\delta_{ik} = 1$ if the observed increment of condition rating for segment k is $(j - i)$

0 otherwise

The log-likelihood function for the ordered probit model is

$$LL = \sum_{k=1}^{K_i} \sum_{(j-i)=0}^{I-1} \delta_{ik} LN \left[\Phi(\mu_{i(j-i+1)} - \beta_i X_k) - \Phi(\mu_{i(j-i)} - \beta_i X_k) \right] \tag{3.17}$$

By maximizing the log-likelihood function given in equation (3.17), the model parameters, β, and thresholds, μ's, can be jointly estimated.

3.1.2.2.3 Composition of the Transition Matrix

The first step in the development of transition matrices for the Markov chain is the estimation of probabilities for increments in condition changes for each condition state. For instance, for condition ratings ranging from 1 (best) to 5 (worst), the possible number of increments for condition state 1 is five (0, 1, 2, 3, and 4) assuming no preservation or improvement activities are performed to upgrade the condition of the facilities. Assuming that m is the total number of condition states, a total of $(m - 1)$ incremental deterioration models are required since the last row in the transition matrix shown in equation (3.3) is regarded as an absorbing state.

Based on the parameters for the ordered probit model estimated from the maximum log-likelihood function given in equation (3.17), the transition probabilities for each segment of wastewater collection systems can be computed as shown in equation (3.18).

$$
\begin{aligned}
&\hat{P}(y_{ik} = 0 \mid X_k, i) = \Phi(\hat{\mu}_{i1} - \hat{\beta}_i X_k) \\
&\hat{P}(y_{ik} = 1 \mid X_k, i) = \Phi(\hat{\mu}_{i2} - \hat{\beta}_i X_,) - \Phi(\hat{\mu}_{i1} - \hat{\beta}_i X_k) \\
&\hat{P}(y_{ik} = 2 \mid X_k, i) = \Phi(\hat{\mu}_{i3} - \hat{\beta}_i X_,) - \Phi(\hat{\mu}_{i2} - \hat{\beta}_i X_k) \\
&\dots \\
&\hat{P}(y_{ik} = I - 1 \mid X_k, i) = 1 - \Phi(\hat{\mu}_{i(I-1)} - \hat{\beta}_i X_k)
\end{aligned}
\tag{3.18}
$$

where, $\hat{P}(y_{ik} \mid X_k, i)$ = transition probability from condition state *i* to *j* for a segment with attribute vector $\boldsymbol{X_k}$

For the maintenance and operation of infrastructure assets, it is desirable to make decisions based on the group of facilities rather than individual facilities. The transition probabilities for groups or the entire network can be computed using the transition probabilities for each facility. According to Ben-Akiva and Lerman (1985), five procedures can be considered for the aggregation of individual analysis results: average individual procedure, classification procedure, statistical differentials procedure, explicit integration procedure, and sample enumeration procedure. In this study, the average individual procedure is used for the estimation of transition probabilities for groups or the entire network. Hence, the transition probabilities of any group are the average values of the transition probabilities for an individual segment.

When the transition probabilities are estimated using the ordered probit model-based approach, the deterioration curve can be drawn based on the values computed using the equation (3.10). In this case, different probability matrices are used for each transition period (year) in the calculation.

3.2 Deterioration-Based Infrastructure Asset Valuation Model

A valuation method that can reflect the condition changes of infrastructure assets is presented in this section. Once the deterioration model is developed using the methods described in Section 3.1, the values of wastewater infrastructure assets can be estimated using the deteriorated value method described herein.

3.2.1 Deteriorated Value (DV) Method

The deteriorated value (DV) method estimates the value of infrastructure assets by multiplying the ratio computed from the difference between the expected condition rating at year n and the best condition rating divided by the maximum condition rating difference, which is the difference between the best rating and the worst rating as shown in equation (3.19).

$$Deteriorated\,value(DV) = B\left(1 - \frac{E(n,P) - best\ rating}{worst\ rating - best\ rating}\right) \tag{3.19}$$

where, B = Base value (historical value or replacement value at base year)

$E(n, P)$ = expected condition rating at age (or stage) n

This method can be used for estimation of the current values of infrastructure assets. For instance, if a condition rating system ranging from 1 (best) to 5 (worst) is used and the expected condition rating at age 20 years is 3, the ratio for the estimation of deteriorated value will be 0.5. Thus, the asset value using the DV method implies that 50% of the original value has been lost over 20 years due to deterioration.

3.2.2 Added Value to Markov Chain Model

When maintenance and repair (M & R) activities are performed on wastewater infrastructure assets, the impacts of these investments should be mirrored in the asset values. This section describes the method that incorporates the M & R investments in the deteriorated value.

3.2.2.1 Classification of Maintenance and Repair Activities

According to GASB 34, the costs for M & R activities can be categorized using three different concepts: maintenance costs, preservation costs, and improvement and addition costs. Maintenance costs are the expenditures for recurring regular work that does not improve the condition of the infrastructure assets. Preservation costs are defined by FHWA (1999) as "the outlays that extend the useful life of an asset beyond its original estimated useful life, but do not increase the capacity or efficiency of the asset." Improvement and addition costs are investments that enhance the capacity or efficiency of the asset. Depending on the accounting methods recommended by GASB 34, these three costs are capitalized or considered as expenses (Table 3.1).

Table 3.1: Accounting methods for different expenditures

M & R costs	Depreciation method	Modified approach
Maintenance	Expense	Expense
Preservation	Capitalize	Expense
Improvements and Additions	Capitalize	Capitalize

As shown in Table 3.1, maintenance costs are recorded as expenses for both methods, and preservation costs are regarded as expenses in the modified approach. According to FHWA (1999), maintenance costs are reported as expenses because maintenance activities do not extend the useful life of the assets, but rather only assist the infrastructure assets reach their estimated useful lives and function effectively throughout that time. Preservation costs are regarded as a capital in the depreciation method, while recorded as expenses in the modified approach. However, preservation costs are investments that improve the performance of the infrastructure assets, thereby increasing the value of the asset. If such investments are not made, the owners of infrastructure assets face a loss in asset value. Thus, preservation costs should be viewed as investments to keep the infrastructure assets performing at the desirable conditions.

3.2.2.2 Expected Total Added Value

To account for the increased asset value generated from the investments for maintenance and repair (M & R) activities, a valuation method for infrastructure assets using the Markov chain-based deterioration model is presented here. This concept was developed based on the methods used for the estimation of rewards associated with Markov chain models (Howard 1960; White 1993; Solberg 2002). The *expected total added value* (*ETAV*), which is the increased value of assets from the M & R investments over n transitions in Markov chain processes, can be obtained by combining the estimated transition costs and the transition probabilities. Transitions can be explained as the changes in infrastructure asset conditions from one condition state to another state during a period. In the Markov chain model, such transitions are explained using probabilities. In this study, the transition costs will represent the expenses required to keep or improve the conditions of wastewater infrastructure assets from state j (condition rating j) to state i (condition rating i), where the condition rating of state i is better than that of state j.

Let $v_i^{(n)}$ be the ETAV for n transitions from the initial state i. Assuming the ETAV to be 0 before any transition, i.e., $v_i^{(0)} = 0$, the ETAV from one-step transition is

$$v_i^{(1)} = \sum_j p_{ij} c_{ij} \tag{3.20}$$

where, $v_i^{(1)}$ = expected total added value for the first transition

p_{ij} = transition probability for the conditions of assets

c_{ij} = transition costs associated with transition probabilities

It should be noted that the matrix manipulation used in equation (3.20) means the multiplication of the corresponding cells in the same row. Using the ETAV for the first transition, the ETAV for n transitions can be expressed as shown in equation (3.21). If matrix notation is used, the ETAV can be expressed as shown in equation (3.22).

$$\begin{aligned} v_i^{(n)} &= \sum_j \{c_{ij} + v_j^{(n-1)}\} p_{ij} \\ &= \sum_j p_{ij} c_{ij} + \sum_j p_{ij} v_j^{(n-1)} \\ &= v_i^{(1)} + \sum_j p_{ij} v_j^{(n-1)} \end{aligned} \tag{3.21}$$

where, $v_i^{(n)}$ = expected total increased value for n transitions

$$\mathbf{v}^{(n)} = \mathbf{v}^{(1)} + \mathbf{P}\mathbf{v}^{(n-1)} \tag{3.22}$$

ETAV can be expressed in matrix form shown in equation (3.23).

$$\begin{bmatrix} v_1^{(n)} \\ v_2^{(n)} \\ \vdots \\ v_m^{(n)} \end{bmatrix} = \begin{bmatrix} v_1^{(1)} \\ v_2^{(1)} \\ \vdots \\ v_m^{(1)} \end{bmatrix} + \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1m} \\ p_{21} & p_{22} & \cdots & p_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ p_{m1} & p_{m2} & \cdots & p_{mm} \end{bmatrix} \begin{bmatrix} v_1^{(n-1)} \\ v_2^{(n-1)} \\ \vdots \\ v_m^{(n-1)} \end{bmatrix} \tag{3.23}$$

By adding the ETAV shown in equation (3.21) to the DV given in equation (3.19), the investments for M & R activities can be reflected in the deterioration-based valuation of wastewater infrastructure assets as expressed in equation (3.24).

$$Deteriorated\ value = B\left(1 - \frac{E(n,P) - best\ rating}{worst\ rating - best\ rating}\right) + \left(v_i^{(1)} + \sum_j p_{ij} v_j^{(n-1)}\right) \tag{3.24}$$

In equation (3.24), $v_i^{(1)}$ is the expected added value that can be obtained from the next transition when a facility is now in condition state i. If the transition is not recurrent over time, only $v_i^{(1)}$ is used for the computation of ETAV in equation (3.24).

3.3 Comparisons of Asset Valuation Methods

In asset valuation, the base value is defined as the initial value (or initial cost) that can be used for the original value before the depreciation or discounting processes. If historical cost data are available, they can be used as the base value. However, in most cases, historical cost data are not well documented for wastewater infrastructure assets. Replacement costs can be used as the base value, which is the case in this study.

For the purpose of illustration and comparison, a "sample" subsystem of 8-inch (200 mm) PVC pipes having a base value of $10,000 is assumed to be installed in year 2001. The assumption for the installation year is made to demonstrate the different trends in asset values when using different valuation methods. The asset values of the sample wastewater infrastructure system are estimated based on the depreciation method using the straight line method, the modified approach, and the deterioration-based valuation method for three different cases; (1) maintenance activities are performed, (2) preservation activities are performed, and (3) improvement activities are performed. For the case in which maintenance activities are performed, two other depreciation methods, i.e., declining balance depreciation and sum-of-years-digits depreciation, as well as the market value method, are included in the comparison.

3.3.1 Deterioration Model

For illustration, a Markov chain-based deterioration model is assumed to be developed using the nonlinear optimization-based approach. The assumptions used in this deterioration model are as follows:

- A zone is assumed to have a six-year period. Within a zone, the transition probability matrix is stationary.
- The condition of the asset does not drop by more than one state in a one-year transition. Thus, the transition probabilities where j is greater than $(i+1)$ are zero.
- No improvement activities are performed over the life of the infrastructure asset. Hence, the transition probabilities for the cells where i is greater than j have null values. Thus, the transition probability matrix $\boldsymbol{P}$ can be expressed as shown in equation (3.25).

$$\mathbf{P} = \begin{bmatrix} p_1 & 1-p_1 & 0 & 0 & 0 \\ 0 & p_2 & 1-p_2 & 0 & 0 \\ 0 & 0 & p_3 & 1-p_3 & 0 \\ 0 & 0 & 0 & p_4 & 1-p_4 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.25}$$

- The relationship between the condition ratings ($Y(t)$) and age (t) is exponentially distributed and the function is obtained from regression analysis as shown in equation (3.26).

$$Y(t) = \exp(0.3061 + 0.0217t) \tag{3.26}$$

Based on the aforementioned assumptions and the nonlinear optimization process given in equation (3.9), the transition probabilities for each zone of the assumed subsystem are estimated and summarized in Table 3.2.

The regression function and related transition probabilities were obtained from the actual condition rating data for 8-inch (200 mm) PVC pipes. However, since the number of data points (12 data points) used for this analysis is not sufficient, these results are not used for further analysis, but rather are used only as an example in this chapter.

Table 3.2: Transition probabilities for sample 8-inch (200 mm) PVC pipes

Age period	Transition Matrix for Zones	p_1	p_2	p_3	p_4	p_5
1 – 6	$\mathbf{P}_1$	0.8487	1	1	1	1
7 – 12	$\mathbf{P}_2$	1	0.9836	0.4865	0.3809	1
13 – 18	$\mathbf{P}_3$	0.9511	0.9708	0.9176	0.1595	1
19 – 24	$\mathbf{P}_4$	0.9710	0.9527	0.9408	0.5141	1
25 – 30	$\mathbf{P}_5$	0.9692	0.9509	0.9101	0.8536	1
31 – 36	$\mathbf{P}_6$	0.9649	0.9403	0.8986	0.8876	1
37 – 42	$\mathbf{P}_7$	0.9414	0.9169	0.8870	0.8949	1
43 – 48	$\mathbf{P}_8$	0.9040	0.8782	0.8596	0.8926	1
49 – 54	$\mathbf{P}_9$	0.8207	0.7952	0.7922	0.8478	1
55 – 60	$\mathbf{P}_{10}$	0.5275	0.5287	0.5693	0.3191	1

Using the transition probabilities and the equation (3.10) for the expected condition ratings, a deterioration curve for the sample subsystem is presented in Figure 3.3.

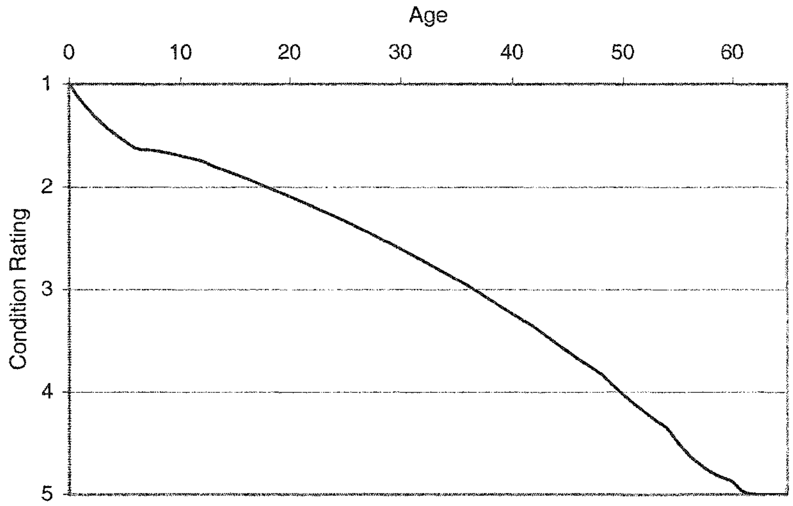


Figure 3.3: Deterioration curve for sample 8-inch (200 mm) PVC pipes

The expected useful life of wastewater infrastructure assets can be calculated using two approaches. On approach uses the expected condition rating given in equation (3.10). When this approach is used, the age that the expected condition rating reaches the worst condition (condition state 5) is determined and used as the expected useful life. Based on this approach, the expected useful life for this sample subsystem is 62 years.

Alternatively, a mathematical approach can be used to compute the expected useful life. The probability of being in condition state 5 (worst condition) after n transitions starting from condition state 1 (best condition) is the value of p_{15} in the n-step transition probability matrix, $\boldsymbol{P}^n$, given in equation (3.7). Thus,

$$P\{\text{being in state 5 after } n \text{ transitions starting from state 1}\} = [\boldsymbol{P}^n]_{15} \qquad (3.25)$$

Let T denote the time (age in year) to reach condition state 5 starting from condition state 1. Then,

$$P\{\text{being in state 5 after } n \text{ transitions starting from state 1}\} = P\{T \le n\} = [\boldsymbol{P}^n]_{15} \qquad (3.26)$$

Since T is a discrete random variable, the expected value of T can be expressed as shown in equation (3.27) (DeVore 1995).

$$\begin{aligned} E(T) &= \sum_{n=1}^{\infty} nP\{T = n\} \\ &= \sum_{n=1}^{\infty} n\left[P\{T \le n\} - P\{T \le (n-1)\}\right] \end{aligned} \qquad (3.27)$$

where, $P\{T \le 0\} = 0$

Therefore, the expected useful life can be estimated by multiplying the number of transitions and the difference of probabilities between p_{15} of $\boldsymbol{P}^n$ and p_{15} of $\boldsymbol{P}^{n-1}$ to infinity. If the expected value for n-transition is less than a pre-determined number (for instance, 0.0001), then the expected useful life can be computed by adding the expected values up to n-transition. The expected useful life based on this approach for the sample 8-inch (200 mm) PVC pipes is 46 years.

Either of the two approaches can be employed for the determination of expected useful life. However, considering the useful life of 70 years for PVC sewer pipes indicated by New South Wales (NSW 1999), the expected condition rating approach, which provides the expected useful life of 62 years, is used to determine the expected useful life of wastewater infrastructure assets in this study.

3.3.2 Description for Valuation Methods

This section describes the valuation methods used for the estimation of infrastructure asset values. The methods of estimation are addressed for three different investment cases for M & R activities.

3.3.2.1 When Maintenance Activities are Performed

This case assumes that only routine maintenance activities are performed during the useful life of the wastewater infrastructure assets. Since the costs for maintenance activities, such as cleaning and root removing, are considered as expenses, the asset value estimated using the modified approach remains the same during the entire useful life. The DV can be estimated using equation (3.19). The asset value follows the same trend provided by the deterioration curve in this case.

3.3.2.1.1 Book Value (BV) - Depreciation Method

The BV can be estimated by subtracting the depreciation costs from the base value. In addition to the straight-line method, the declining balance method and the sum-of-years-digits method are explored to investigate the effects of the selection of the different depreciation methods on the valuation of wastewater infrastructure assets.

- Straight-Line (SL) Method

The base value was depreciated based on the expected useful life of 62 years and the assumed salvage value of \$0 for 8-inch (200 mm) PVC pipes. Given the SL depreciation equation, the BV can be computed as shown in equation (3.28) and (3.29).

$$d_n = \frac{B-S}{N} = \frac{B}{62} \tag{3.28}$$

$$BV_n = B - nd_n = \frac{B}{62}(62-n) \tag{3.29}$$

where, d_n = depreciation charge during year n

B = base value

S = salvage value at the end of useful life

N = useful life (62 years based on deterioration model)

BV_n = book value at the end of year n

- Declining Balance (DB) method

Using the 150% DB ratio, the BV can be obtained as shown in equation (3.30).

$$BV_n = B(1-\alpha)^n = B\left(1-\frac{1.5}{62}\right)^n = (0.97581)^n B \tag{3.30}$$

where, α = depreciation rate (=1.5/N = 1.5/62)

In this method, the depreciation method is switched to the SL method in the year when the amount of the depreciation from the SL method is greater than or equal to the amount from the DB method.

- Sum-of-Years-Digits (SOYD) method

The SOYD method uses the base value, the salvage value, the useful life, and the current age to find the BV of the assets. Assuming salvage value as $0 at the end of useful life, the BV for 8-inch PVC pipe based on the SOYD method can be expressed as shown in equation (3.31).

$$\begin{aligned} BV_n &= B - \left[\frac{2(B-S)}{N}\right]n + \left[\frac{B-S}{N(N+1)}\right]n(n+1) \\ &= B - \frac{nB}{31} + \frac{n(n+1)B}{3906} \end{aligned} \tag{3.31}$$

3.3.2.1.2 Market Value (MV)

The imputed (or implied) MV technique is applied in this study, which is useful when adequate information for current and historical cost (or value) data is unavailable. The imputed MV at the end of year n can be calculated using the equation given in equation (3.32) (Sullivan et al. 2002).

MV_n = [Present Worth at the end of year n of remaining capital recovery amounts] +

[Present Worth at end of year *n* of original market value at end of useful life]

= [(B(A/P, i%, N) – S(A/F, i%, N)](P/A, i%, N-n) + S(P/F, i%, N-n)

$$= \left(B \times \frac{i}{1-(1+i)^{-N}} - S \times \frac{i}{(1+i)^{N}-1} \right) \times \frac{1-(1+i)^{-(N-n)}}{i} + \frac{S}{(1+i)^{N-n}} \tag{3.32}$$

where, B = base value

S = salvage value at the end of useful life

(A/P, i%, N): Capital recovery factor $\left(= \dfrac{i}{1-(1+i)^{-N}} \right)$

(A/F, i%, N): Sinking fund factor $\left(= \dfrac{i}{(1+i)^{N}-1} \right)$

(P/A, i%, N-n): uniform series present worth factor $\left(= \dfrac{1-(1+i)^{-(N-n)}}{i} \right)$

(P/F, I%, N-n): Single payment present worth factor $\left(= \dfrac{1}{(1+i)^{N-n}} \right)$

For estimation of the MV of the assets, inflation rate, *i*, is required. The popular references to reflect the price changes in the economy are the Consumer Price Index (CPI) and the Producer Price Index (PPI) which are calculated monthly by the Bureau of Labor Statistics of the U.S. Department of Labor. However, since the Construction Cost Index (CCI) from Engineering News Record (ENR) better reflects the price changes in the construction industry, the CCI was applied to determine the inflation rate for the calculation of MV. The average price change rate (inflation) for the previous 62 years is 5.34% (ENR CCI 2003), which was assumed to be constant all through the useful life of the sample assets. Using the average inflation rate, the market values of 8-inch (200 mm) PVC pipes can be calculated using equation (3.33).

$$\begin{aligned} MV_n &= \left(\frac{0.0514B}{1-1.0514^{-62}} \right) \left(\frac{1-1.0514^{-(62-n)}}{0.0514} \right) \\ &= 1.04680 \times \left(1-1.0514^{-(62-n)}\right) \times B \end{aligned} \tag{3.33}$$

3.3.2.2 When Preservation Activities are Performed

The costs for preservation activities, such as grouting or spot repair, are capitalized when the depreciation method is used but are considered as expenses for the modified approach. Thus, the book value based on the depreciation method is affected by preservation costs, whereas the modified approach-based value does not change.

Assuming that preservation activities are applied every five years and that the condition states of infrastructure assets rise one level higher, the ETAV in equation (3.24) becomes $v_i^{(1)}$ and can be obtained from equation (3.34).

$$\begin{aligned} ETAV = v_i^{(1)} &= \sum_j p_{ij} c_{ij} \\ &= \begin{bmatrix} p_1 & 1-p_1 & 0 & 0 & 0 \\ p_1 & 1-p_1 & 0 & 0 & 0 \\ 0 & p_2 & 1-p_2 & 0 & 0 \\ 0 & 0 & p_3 & 1-p_3 & 0 \\ 0 & 0 & 0 & p_4 & 1-p_4 \end{bmatrix} \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ c_{21} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \\ &= p_1 c_{21} \end{aligned} \tag{3.34}$$

In the example described in this chapter, the condition of 8-inch (200 mm) PVC pipes deteriorates towards condition state 2 after five years. As preservation activities upgrade the condition state by one level (i.e., condition sate 1), only the c_{21} cell in the transition cost matrix has a value. The transition cost matrix can be different depending on the effects of preservation activities on the condition states of the assets.

3.3.2.3 When Improvement Activities are Performed

When improvement activities such as rehabilitation and replacement are performed, the related investments are capitalized in both the book value and the modified approach-based value. Assuming that improvement activities are performed every 20 years, which returns the condition states of infrastructure assets to the initial condition, the ETAV can be estimated using equation (3.35).

$$ETAV = v_i^{(1)} = \sum_j p_{ij} c_{ij}$$

$$= \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ c_{21} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \qquad (3.35)$$

$$= c_{21}$$

The transition matrix in equation (3.35) implies the returning of condition states to the initial condition state. The 8-inch (200 mm) PVC pipes reach condition state 2 after 20 years as shown in Figure 3.3. Thus, the improvement activities upgrade the state of the pipes from condition 2 to condition 1 making c_{21} the only value in the transition cost matrix. The composition of transition cost matrix is based on the effects of improvement activities. For instance, if the improvement activities are performed for the pipes in condition state 5, only c_{51} cell has a value in the matrix.

3.3.3 Modeling Results and Implications

The values of wastewater infrastructure assets based on the different valuation approaches are presented in this section. Depending on the four different investment cases, the values of the sample subsystem of 8-inch (200 mm) PVC pipes are estimated and compared, and the variations of asset values when using different valuation methods are discussed. Based on the maintenance activities undertaken, the values of the assets will be different, and hence have different implications for the managers involved in decision-making regarding future investments and budget allocations for the renewal of these assets.

3.3.3.1 When Maintenance Activities are Performed

The changes in values over the useful life of the asset, obtained from different valuation methods, are presented in Figure 3.4.

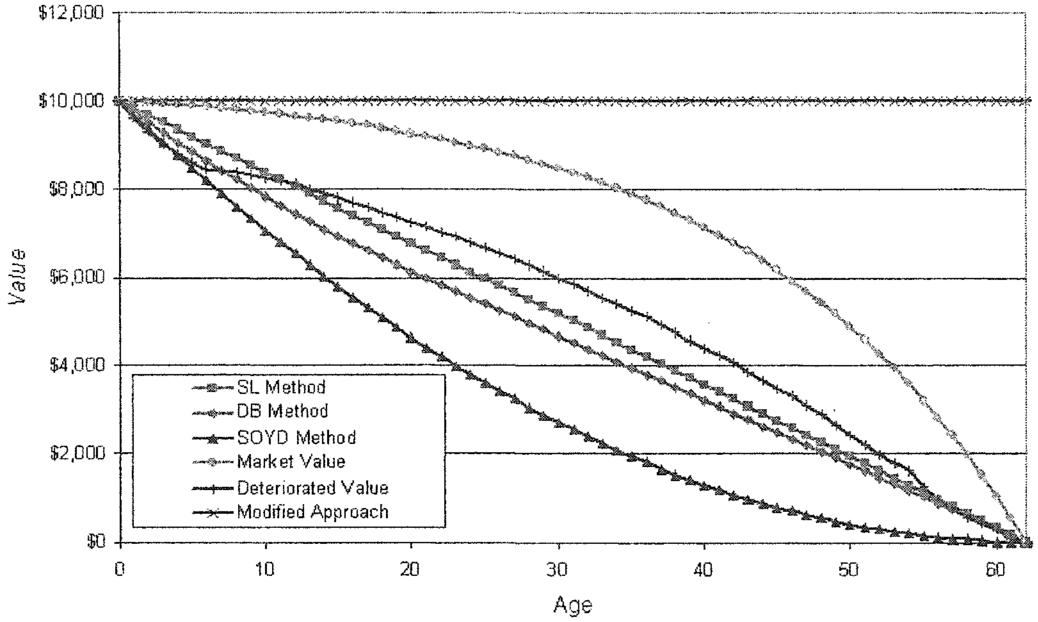


Figure 3.4: Asset values when maintenance activities are performed

As shown in Figure 3.4, the book value using the SL depreciation method decreases at a constant rate. The DB depreciation results in a greater reduction in value during the early years than during the later years of the useful life. A switch is made to the SL method from age 22 to the end of the useful life. The SOYD method depreciates the values of the asset more rapidly in the early years than does the DB method, and the amounts of depreciation are greater than those of the DB method. On the other hand, the MV curve shows that the value decreases gradually at the beginning, and at a rapid rate as the asset reaches the end of its useful life. However, the pattern of the MV curve can change, depending on the selection of an inflation rate.

The aforementioned valuation methods do not reflect the changes of the condition of the infrastructure assets. The deterioration-based valuation methods reflect the trend shown in the deterioration curve in the changes of asset values over time. The deteriorated value method follows exactly the same trend as the deterioration curve shown in Figure 3.3.

The ages at which the asset is at 90%, 75%, 50%, and 25% of the base value for each valuation method are determined using linear interpolation and presented in Table 3.3. The comparisons are also presented graphically in Figure 3.5.

Table 3.3: Ages for remaining percentage of base value for maintenance activities (years)

Percentage of base value	Book Value			Market Value	Deteriorated Value
	Straight Line	Declining Balance	Sum-of-Years-Digits		
90%	6.2	4.3	3.2	24.0	3.1
75%	15.5	11.7	8.4	37.8	17.8
50%	31.0	27.7	18.3	49.6	36.5
25%	46.5	44.9	31.3	56.8	49.7

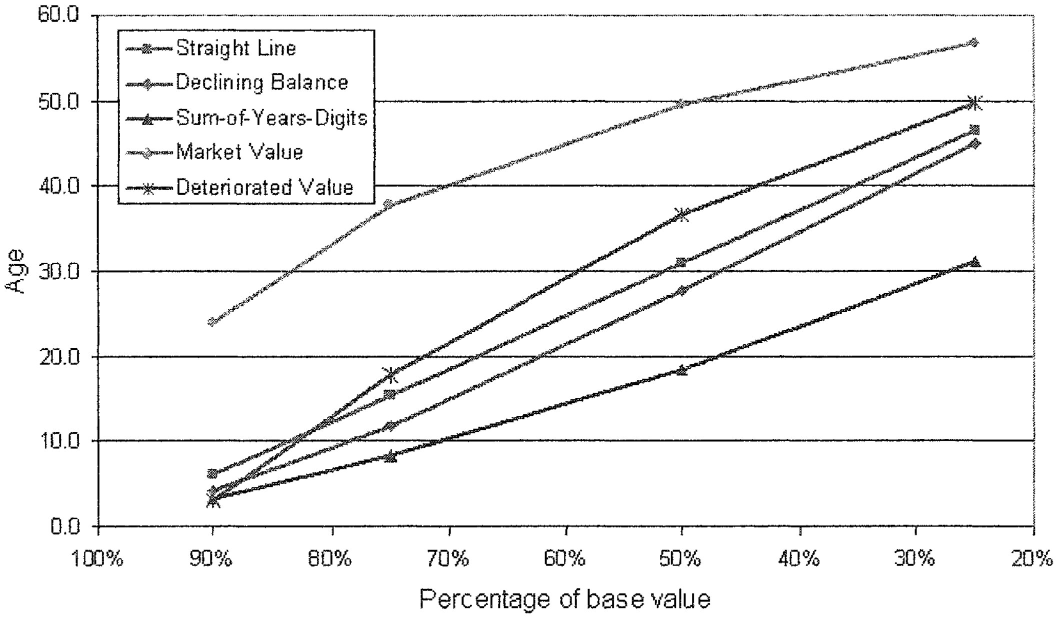


Figure 3.5: Comparison of ages for remaining percentage of base value

From Table 3.3 and Figure 3.5, it can be observed that, depending on the selection of a valuation method, the variation of the ages estimated from the valuation methods is significant, particularly when the assets are "aged" to the end of the expected useful life.

The value of an asset reaches 90% of its base value in about 1/10, 1/15, 1/20, and 2/5 of the useful life when using the SL method, the DB method, the SOYD method, and the MV method, respectively. The SL method depreciates 50% of the base value in about 1/2 of the useful life, whereas the DB method, the SOYD method, and the MV method estimate 50% loss in about 7/15, 3/10, 5/6 of the useful life, respectively. The asset loses its last 25% value in about 1/4, 1/4, 1/2, and 1/10 of the useful life when using the SL method, the DB method, the SOYD method, and MV method respectively. Thus, municipalities wanting to impose less depreciation or a higher asset value at an early stage of an asset's useful life may wish to use the MV method for the valuation of their wastewater infrastructure assets. On the other hand, municipalities wanting less depreciation during the later stage of an asset's useful life can employ the SOYD method.

In Figure 3.6, the SL method, the most common depreciation method, and the DV method are compared in terms of the ages at which the wastewater infrastructure assets reach 90%, 75%, 50%, and 25% of the base value.

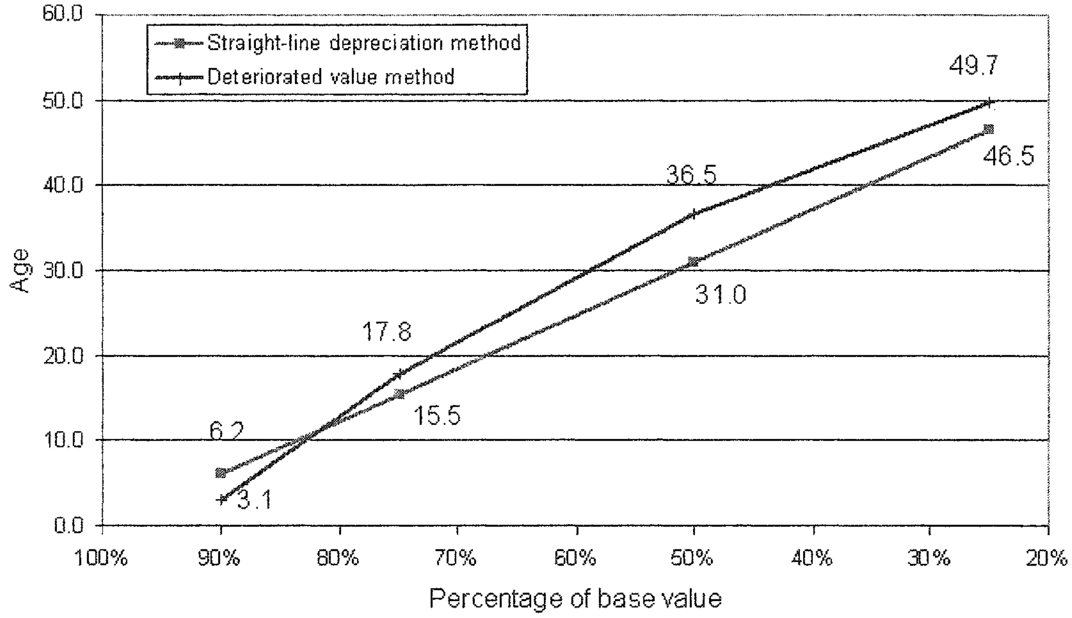


Figure 3.6: Comparison between SL method and DV method

As shown in Figure 3.6, the DV method depreciates the value of assets more slowly than the SL method over the useful life, which means that the SL method may overestimate the depreciation value. Accordingly, the asset value may be underestimated when using the SL method, which could result in underestimated infrastructure asset values in financial reports. In the case of the modified approach, the base value does not change when there are no M & R activities. Generally, the DV method discounts the asset values in a gradual manner in the early years and then rapidly depreciates the value during the later years. Thus, when valuating the assets using the DV method, the asset "loses" 50% of its value during the last 2/5 of the useful life.

3.3.3.2 When Preservation Activities are Performed

For the estimation of asset values using the depreciation method, the modified approach, and the DV method, it was assumed that $500 was invested every five years on preservation activities. The comparison of the asset values using the three valuation methods is shown in Figure 3.7.

The modified approach-based value does not change throughout the useful life since the preservation costs are considered as expenses in the modified approach. The book value decreases $161 per year due to depreciation and increases $500 every five years due to the preservation costs. The book value at age 62 is $6,000. When the DV method is used, the deteriorated value sees a decrease due to deterioration and increases due to preservation costs. However, the amount of increase is not always $500 since the transition probabilities used for the computation of the ETAV are not always one. The deteriorated value at year 62 is $4,007. Therefore, with respect to the deteriorated value at age 62, the book value and the modified approach-based value are 50% and 150% greater than the deteriorated value respectively, which demonstrates that there are significant variations in infrastructure asset values depending on the valuation method used.

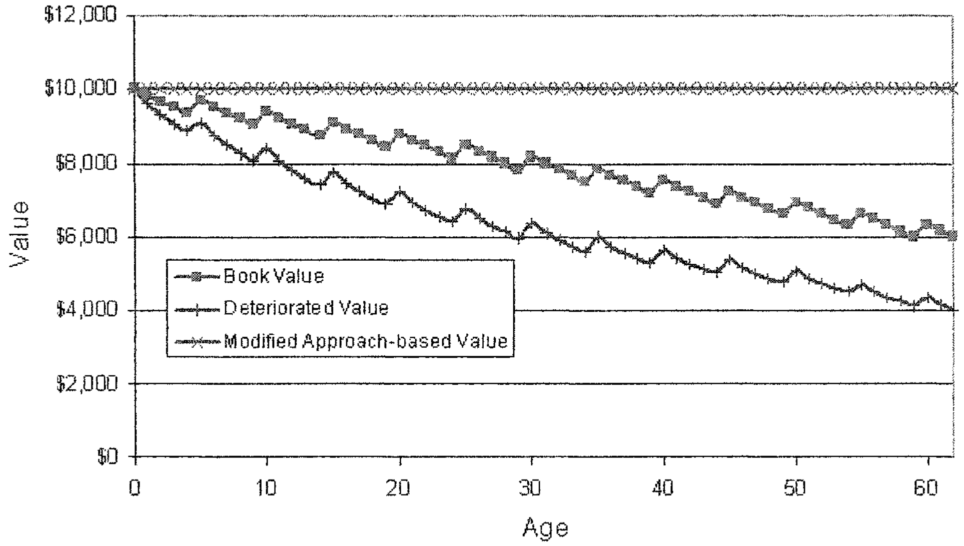


Figure 3.7: Asset values when preservation activities are performed

3.3.3.3 When Improvement Activities are Performed

The asset values were estimated based on an assumption that $2,000 is invested every 20 years for improvement activities. In this case, the amount of $2,000 is reflected in all of the three values, i.e., the book value, the deteriorated value, and the modified approach-based value. The asset values estimated using the three valuation methods are presented in Figure 3.8. As shown in Figure 3.8, there are increases as shown by points A, B, and C in asset values as the improvement activities are performed. The asset values estimated from the depreciation method and the DV method decrease after the increases, whereas the value obtained from the modified approach remains the same until the next improvement activities are performed.

The modified approach-based value increases $2,000 every 20 years resulting in a value of $16,000 at the end of the useful life. The book value repeats a decrease and an increase due to depreciation and improvement costs. The book value at age 62 is $6,000. The deteriorated value decreases, following the pattern of the deterioration curve for 8-inch (200 mm) PVC pipes. A value of $2,000 is added to the deteriorated value every 20 years and the value decreases again following the same pattern as before since the condition of the assets is returned to the initial condition (state 1) after the improvement activities. The estimated deteriorated value at the end of the useful life is $8,404. Therefore, at age 62, the book value is 29% less than the deteriorated value, while the modified approach-based value is 90% greater than the deteriorated value.

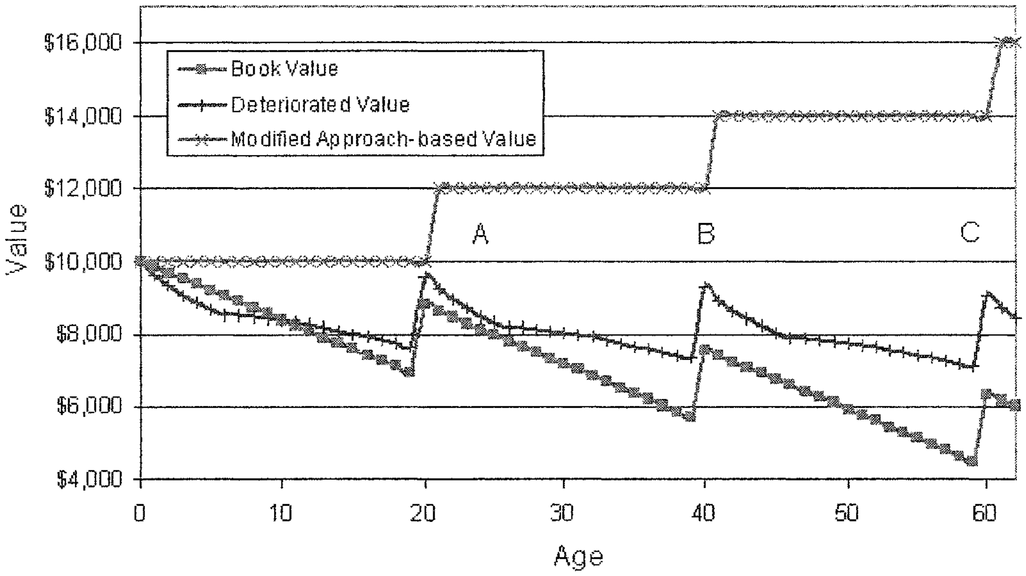


Figure 3.8: Asset values when improvement activities are performed

3.4 Chapter Summary

This chapter discussed the methodologies used for the development of Markov chain-based deterioration models for wastewater infrastructure assets, including the theoretical background of two approaches adopted for the estimation of transition probabilities, i.e., the nonlinear optimization-based approach and the ordered probit model-based approach. A valuation method reflecting deterioration of the infrastructure assets was also presented. The DV method and other valuation methods, such as the depreciation method and the modified approach, were used for the estimation of asset values for a "sample" system based on three different investment cases for M & R activities over the useful life. The estimation results of the asset values indicated that substantial variations can be observed depending on the valuation method used.

CHAPTER 4. APPLICATION OF LIFE CYCLE COST ANALYSIS FOR THE VALUATION OF WASTEWATER INFRASTRUCTURE ASSETS

Life cycle cost analysis (LCCA) can provide decision-makers with reliable cost information for future asset investments. Utilizing optimization techniques such as linear programming, integer programming, and dynamic programming, LCCA can convey knowledgeable and accurate comparisons of the available options regarding decisions for both a single asset improvement at a given time as well as cost-effective long-range planning decisions at various stages of the life of an asset.

Limited resources for the management of infrastructure assets are always a factor to consider during the planning of future investments, and knowing the optimal alternatives will enable prioritization schemes for better resource allocation. Therefore, given a limited budget for the decision-making processes, projects that have first priority can be determined based on the prioritization schemes. Using the maintenance and repair (M & R) alternatives for wastewater infrastructure assets obtained from the LCCA and the prioritization process, the future values of wastewater infrastructure assets can be estimated using the equations and methods described in Chapter 3.

Several issues related to LCCA and procedures to find future asset values in association with the M & R alternatives recommended by LCCA are presented in this chapter. The background theory of dynamic programming, which is used for the optimization of competing alternatives for M & R activities, is presented first. In the optimization processes using dynamic programming, it is desirable to apply different transition probabilities to account for the effects of different types of M & R activities. The composition of transition probabilities for routine maintenance, preservation activities, and improvement activities such as rehabilitation and replacement then follows including a discussion of some of the rehabilitation techniques applicable for wastewater collection systems. Finally, there are discussions regarding the application of the optimal alternatives for the estimation of the values of wastewater infrastructure assets.

4.1 Dynamic Programming

4.1.1 Concepts of Dynamic Programming

Dynamic programming is one of the optimization techniques to find optimal solutions during the decision-making process. While other optimization techniques such as linear programming find the optimal solutions for the entire problem simultaneously, dynamic programming breaks down the entire problem of optimization into subsets of the problem. Then, optimization using dynamic programming includes each subset individually until the optimal solutions for the entire problem are found. This breakdown procedure is called *decomposition* and the decomposed subsets of the problems are called *stages*. Each stage has a number of *states* associated with the stage and *decisions* related to the states (Smith 1991).

The concept of dynamic programming can be explained using a network problem (Winston 1994). Suppose that a salesman has to travel from City 1 to City 27 in six days and he has five cities for each day's visit as shown in Figure 4.1.

The solution he wants to find for this travel is the shortest path from City 1 to City 27. In this problem, each day, each city, and the paths between the cities can be defined as stages, states, and decisions, respectively. When using dynamic programming, the computations to find the optimal solutions are made backward from the last stage. Thus, for the travel from Day 6 (Stage 6) to Day 7 (Stage 7), the shortest path between the cities (states) in Stage 6 and Stage 7 are determined starting from Stage 7. For the computation for Stage 5, the distances of possible paths (decisions) in Stage 5 are added to the results obtained from the previous computations. Through this process, the shortest path from Cities 17, 18, 19, 20, and 21 to City 27 can be obtained. Using these recursive calculations for all the cities (states) in each stage until City 1 is reached, the shortest path from City 1 to City 27 can be found.

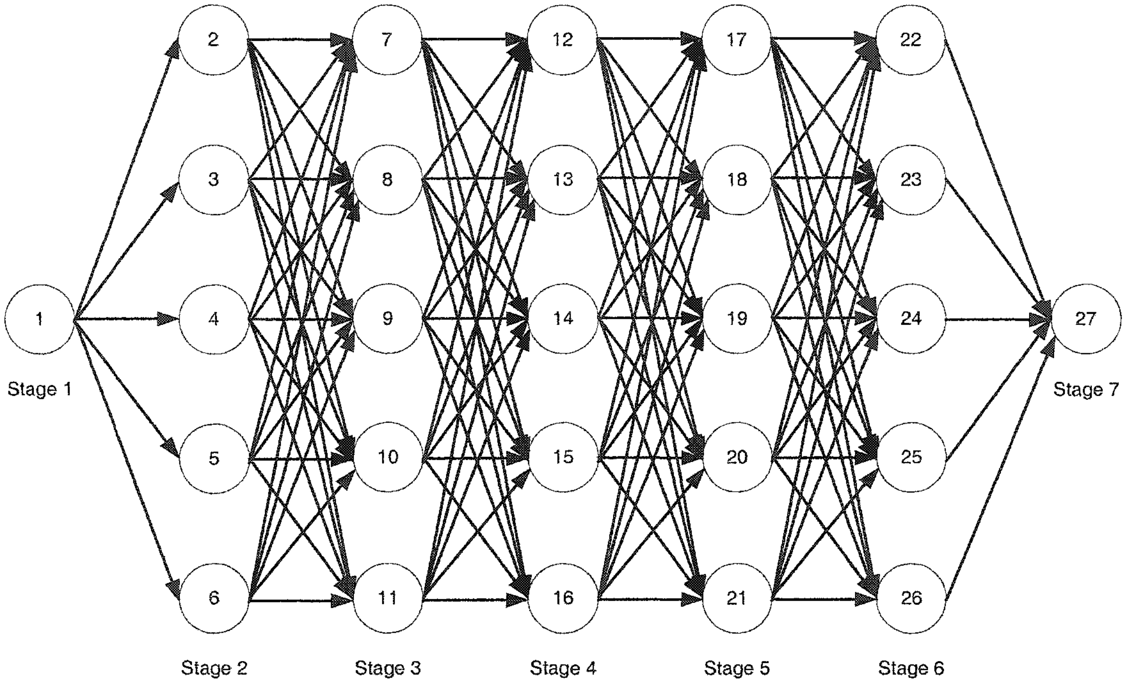


Figure 4.1: Network example for dynamic programming (Winston 1994)

The conceptual progress of the computation using dynamic programming is shown in Figure 4.2. The use of dynamic programming provides significant computational efficiency. When using the explicit enumeration for the given network problem, it requires 15,625 additions and 3,124 comparisons to find the best route. However, dynamic programming requires 105 additions and 84 comparisons for the same problem.

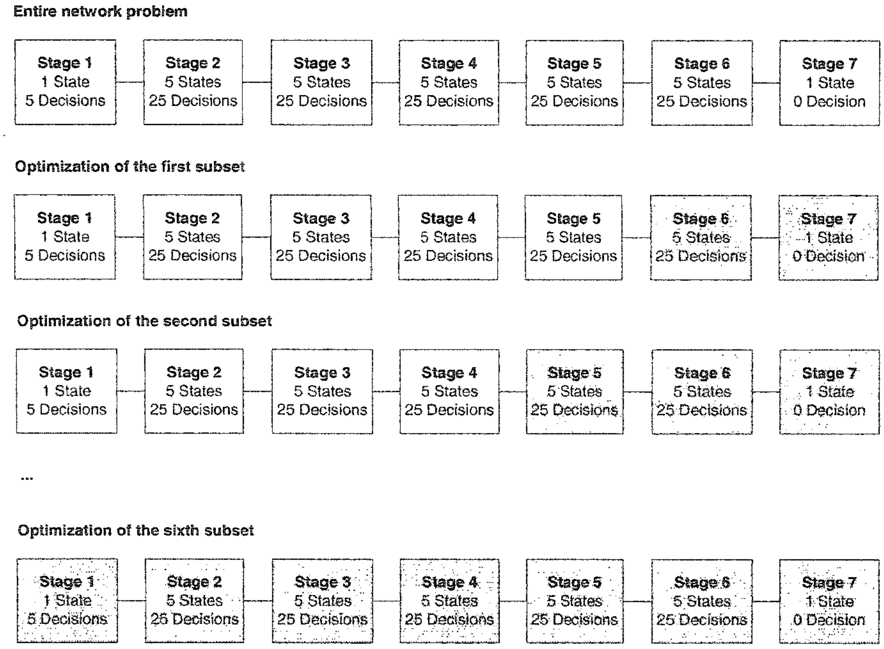


Figure 4.2: Conceptual computation steps of dynamic programming

4.1.2 Probabilistic Dynamic Programming

The aforementioned example is a deterministic dynamic programming problem which can be formulated using the equation (4.1) (Winston 1994).

$$f_n(\mathit{current\ state}) = \min_{\mathit{all\ feasible decisions}} (or\ \max)\{\mathit{costs}\ (\mathit{or\ rewards})\ \mathit{during\ current\ stage} + f_{n+1}(\mathit{new\ state})\} \quad (4.1)$$

where, f_n, f_{n+1} = optimal solution for stage n and $(n+1)$

When the costs during the current stage or the change of states during the period is not known with certainty, these situations can be expressed using probabilities resulting in probabilistic dynamic programming problems. In the problem of the selection of optimal solutions for maintenance and repair (M & R) of wastewater infrastructure assets that provide the feasible alternatives with minimum costs, the costs required during the current stage is known with certainty whereas the next period's state is not. This uncertainty associated with the change of states can be described with the transition probabilities in Markov chain model.

The transition probability for infrastructure assets represented in a matrix form can be estimated based on the methods used for the development of deterioration models for infrastructure assets described in Chapter 3. However, since the transition probabilities obtained from the deterioration modeling is based on the assumption that no preservation or improvement activities have been performed, different transition probabilities are needed for preservation and improvement activities.

Let us suppose that the transition probability obtained from deterioration modeling can be expressed in a matrix form, ***P***, as shown in equation (4.2).

$$P = \begin{bmatrix} p_{11} & 1-p_{11} & 0 & 0 & 0 \\ 0 & p_{22} & 1-p_{22} & 0 & 0 \\ 0 & 0 & p_{33} & 1-p_{33} & 0 \\ 0 & 0 & 0 & p_{44} & 1-p_{44} \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{4.2}$$

This transition matrix can be used for routine maintenance or "no action" for infrastructure assets. Therefore, in the case of wastewater infrastructure asset, "routine cleaning" can apply the transition matrix given in equation (4.2) for the analysis using probabilistic dynamic programming.

For preservation activities such as grouting and spot repair, and improvement activities such as rehabilitation and replacement, transition matrices can be formulated based on the transition matrix of the routine maintenance activities or on the engineering judgement of the experts. According to Madanat (1991), Madanat and Ben-Akiva (1994) and Guignier and Madanat (1999), the transition probability for the rehabilitation of pavement systems, particularly for overlay, can be obtained by shifting down the transition probabilities in the first row of the transition matrix. Depending on the extent of the shifts and engineering judgement considering the effects of the rehabilitation, four transition matrix types can be formulated. However, in the case of wastewater infrastructure asset, since rehabilitation activities such as sliplining and cured-in-place pipe (CIPP) lining can improve the condition state to the best condition (condition 1), these techniques are employed for the composition of the transition matrix for preservation activities in this study.

(1) One shift and use of the transition probabilities from routine maintenance.

The probabilities in the first row of the transition matrix for routine maintenance are repeated for the first row of the transition matrix for preservation activities and the probabilities of the upper four rows are shifted down to the fifth row as shown in equation (4.3). This transition matrix implies that the preservation activities can upgrade the condition states of wastewater infrastructure assets one level high from condition states 2, 3, 4, and 5. The deterioration rates of condition states 2, 3, 4, and 5 are lowered by following the rates of the condition states 1, 2, 3, and 4 of the deterioration with routine maintenance.

$$P = \begin{bmatrix} p_{11} & 1-p_{11} & 0 & 0 & 0 \\ p_{11} & 1-p_{11} & 0 & 0 & 0 \\ 0 & p_{22} & 1-p_{22} & 0 & 0 \\ 0 & 0 & p_{33} & 1-p_{33} & 0 \\ 0 & 0 & 0 & p_{44} & 1-p_{44} \end{bmatrix} \tag{4.3}$$

(2) A number of shifts and use of the transition probabilities from routine maintenance.

The probabilities in the first row of the transition matrix for routine maintenance are repeated more than one row from the top in the transition matrix for preservation activities. The remaining rows of the transition matrix for preservation activities are copied from the top row of the transition matrix for routine maintenance. In the case shown in equation (4.4), the probabilities in the first, second, and third rows are repetitions of the probabilities in the first row of the transition matrix given in equation (4.2). The fourth and fifth rows of the matrix are filled with the transition probabilities of the second and third rows in the matrix in (4.2). The transition matrix shown in equation (4.4) means that preservation activities can upgrade the condition states 2 and 3 to condition state 1. Condition states 4 and 5 are upgraded to conditions 2 and 3, respectively, when the preservation activities are performed. The deterioration rates in this case follow the rates of condition state 1 (for condition state 2 and 3), condition state 2 (for condition state 4), and condition state 3 (for condition state 5) of the routine maintenance.

$$P = \begin{bmatrix} p_{11} & 1-p_{11} & 0 & 0 & 0 \\ p_{11} & 1-p_{11} & 0 & 0 & 0 \\ p_{11} & 1-p_{11} & 0 & 0 & 0 \\ 0 & p_{22} & 1-p_{22} & 0 & 0 \\ 0 & 0 & p_{33} & 1-p_{33} & 0 \end{bmatrix} \tag{4.4}$$

(3) One shift and use of the transition probabilities in the first row of the transition matrix for routine maintenance.

The probabilities in the first row of the transition matrix for routine maintenance are repeated for the first and second rows of the transition matrix for preservation activities. These probabilities are also used for the third, fourth, and fifth rows of the transition matrix for preservation activities with the transitions of down-grade, one by one, as condition states become worse as shown in equation (4.5). This transition matrix implies that the preservation activities can upgrade the condition states of wastewater infrastructure assets one level higher from condition states 2, 3, 4, and 5, as for the first case. In addition to the condition upgrade, the deterioration rates for condition ratings 3, 4, and 5 are lowered to follow the deterioration of condition state 1 for routine maintenance after the preservation activities are performed.

$$P = \begin{bmatrix} p_{11} & 1-p_{11} & 0 & 0 & 0 \\ p_{11} & 1-p_{11} & 0 & 0 & 0 \\ 0 & p_{11} & 1-p_{11} & 0 & 0 \\ 0 & 0 & p_{11} & 1-p_{11} & 0 \\ 0 & 0 & 0 & p_{11} & 1-p_{11} \end{bmatrix} \tag{4.5}$$

(4) A number of shifts and use of the transition probabilities in the first row of the transition matrix for routine maintenance.

The transition matrix for this case is composed in the same manner used for equation (4.4). However, the probabilities in the first row of the transition matrix for routine maintenance are used. This matrix shows that when preservation activities are performed, the condition state 2 is upgraded by one level and condition states 3, 4, and 5 are upgraded by two levels. After the preservation activities are performed, the deterioration rates follow the pattern of the deterioration of condition state 1 of the routine maintenance case.

$$P = \begin{bmatrix} p_{11} & 1-p_{11} & 0 & 0 & 0 \\ p_{11} & 1-p_{11} & 0 & 0 & 0 \\ p_{11} & 1-p_{11} & 0 & 0 & 0 \\ 0 & p_{11} & 1-p_{11} & 0 & 0 \\ 0 & 0 & p_{11} & 1-p_{11} & 0 \end{bmatrix} \qquad (4.6)$$

In the case of replacement or reconstruction, the transition probability can be composed based on the assumption that the condition states after the replacement return to the initial condition. The transition matrix based on this assumption can be expressed as shown in equation (4.7) (Cesare et al. 1992).

$$P = \begin{bmatrix} 1.0 & 0 & 0 & 0 & 0 \\ 1.0 & 0 & 0 & 0 & 0 \\ 1.0 & 0 & 0 & 0 & 0 \\ 1.0 & 0 & 0 & 0 & 0 \\ 1.0 & 0 & 0 & 0 & 0 \end{bmatrix} \qquad (4.7)$$

If there are uncertainties about the returning of the condition states to the initial state, the transition probabilities can be divided into two probabilities based on the confidence level. For example, as presented by Cesare et al. (1992), if the confidence level for the condition state returning to the initial condition is 90%, the transition matrix for the improvement activities can be expressed as the equation (4.8).

$$P = \begin{bmatrix} 0.9 & 0.1 & 0 & 0 & 0 \\ 0.9 & 0.1 & 0 & 0 & 0 \\ 0.9 & 0.1 & 0 & 0 & 0 \\ 0.9 & 0.1 & 0 & 0 & 0 \\ 0.9 & 0.1 & 0 & 0 & 0 \end{bmatrix} \tag{4.8}$$

Where the confidence level is not available or difficult to determine, the probabilities in the first row of the transition matrix for routine maintenance can be used as shown in equation (4.9) as was done by Madanat and Ben-Akiva (1994).

$$P = \begin{bmatrix} p_{11} & 1-p_{11} & 0 & 0 & 0 \\ p_{11} & 1-p_{11} & 0 & 0 & 0 \\ p_{11} & 1-p_{11} & 0 & 0 & 0 \\ p_{11} & 1-p_{11} & 0 & 0 & 0 \\ p_{11} & 1-p_{11} & 0 & 0 & 0 \end{bmatrix} \tag{4.9}$$

In the case of the wastewater infrastructure assets, Wirahadikusumah (1999) presented transition probabilities for different M & R activities based on the assumptions that each M & R alternative extends the useful life of the sewer pipes a certain amount. However, in this work, it was not clearly described how the assumptions were changed into quantitative numbers of transition probabilities.

Using the aforementioned probabilities for different M & R activities, the probabilistic dynamic programming problem for the selection of the optimal alternatives with minimum costs for wastewater infrastructure assets can be formulated as shown in equation (4.10) (Winston 1994).

$$f_n(i) = \min_a \{C_n(i,a) + \alpha \sum_j p(j \mid i,a,n) f_{n+1}(i)\} \tag{4.10}$$

where, $f_n(i)$ = minimum expected costs that are required during stages n, $n+1$, …, end of the problem, given that the state at the beginning of stage n is i.

a = alternatives (decisions) that are feasible when the state at the beginning of stage n is i.

$C_n(i, a)$ = expected costs during stage n, given that the current state is i and alternative a is chosen.

α = discount rate

$p(j \mid i, a, n)$ = probability that the next period's state will be j, given that the current (stage n) state is i and alternative a is chosen.

$\sum_j p(j \mid i,a,n) f_{n+1}(i)$ = expected costs from stage $(n+1)$ to the end of the problem.

4.1.3 Markov Decision Process

In the problems of dynamic programming, where the stages are represented by time, it is required to determine the length of time considered for the analysis. This time period is called the *horizon length.* The problems using probabilistic dynamic programming with infinite horizon length are called *Markov Decision Processes* (MDPs) (Winston 1994). In MDPs, the state of the next stage depends only on the state of the current stage and on the decision made during the current stage rather than previous states and decisions. The infrastructure assets are assumed to be used infinitely if they are maintained well enough to provide appropriate service to the public. Decision-making processes regarding M & R activities for infrastructure assets thus can be viewed as MDPs.

MDPs consist of four components: state space, decision set, transition probability, and expected costs (or rewards for maximization problems). In the case of the selection of optimal M & R alternatives for wastewater infrastructure assets, the state space, S, can be a set, $S = \{1, 2, \ldots, \mathrm{I}\}$, representing the condition ratings of the sewer pipes. The decision set includes the possible M & R alternatives for wastewater infrastructure assets, such as routine cleaning, grouting, and open-cut replacement. The transition probabilities can be obtained using the concepts addressed in the previous section. The expected costs are the expenditures needed when the condition state is i and one of the M & R activities is chosen.

The goal of MDP problems is to find the optimal policy with which decisions are made at each stage. For the determination of the optimal policy for MDPs, three methods can be used: policy iteration, linear programming, and value iteration (successive approximations). Among the three methods, the value iteration method is applied for the selection of optimal alternatives in this study. Even though the value iteration method approximates the optimal solutions, it provides satisfactory approximation of the minimum expected discounted cost, with less computational efforts needed by the policy iteration method and the linear programming method (Winston 1994). Detailed procedures of the value iteration method are presented later in this chapter.

4.2 Maintenance and Repair Alternatives for Wastewater Infrastructure Assets

With the increased interest in the maintenance of sewer collection systems and the development of techniques and technologies in M & R methods, various alternatives are available for the M & R of wastewater infrastructure assets. Some of the M & R alternatives considered in this study are extracted from the WEF-ASCE manual (1994) and described in the following sections.

4.2.1 Cleaning

Cleaning of the sewer pipes removes the unnecessary material accumulated inside the pipe. The purposes of the sewer cleaning are to mitigate the blockage of the pipes, secure the hydraulic capacity, reduce the pollution and odor, and provide good work conditions for sewer inspections and rehabilitation (Knott 1989 and 1990).

Common methods for the cleaning alternative of wastewater infrastructure assets are jet rodding, rodding, winching or dragging, cutting, and manual or mechanical digging. Jet rodding applies high-pressured water to remove materials and to transport them to the downstream manholes. Rodding is used for smaller diameter pipes to clear the blockage by manual push-and-pull movements. Winching or dragging inserts a bucket in the pipe through a manhole and pulls the bucket from the manhole at the other side. Cutting is a technique that uses high-pressured water jet cutters for the removal of roots intruded in the sewer pipes. Manual or mechanical digging removes the accumulated materials by entering the large-size sewer pipes and clearing the pipes manually or mechanically.

4.2.2 Grouting

Grouting is a technique to seal leaking joints or small holes in the pipes. The loose soil around the leaking joints or holes is stabilized with chemicals to reduce potential infiltration, which accelerates the deterioration of sewer pipes. For small and medium-size pipes, the grouting is performed using the equipment shown in Figure 4.3.

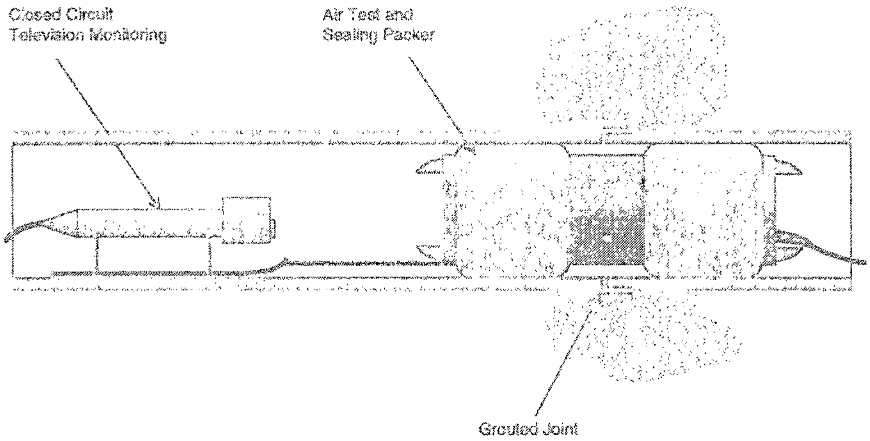


Figure 4.3: Internal grouting equipment (WEF-ASCE 1994)

The grouting equipment first tests the stability of the joints by inflating the rubber collars at both ends of the equipment. If the joint has a leaking problem, chemicals are pumped to solidify the surrounding ground. Even though the grouting costs less than other repair alternatives, it has a limitation that it cannot improve the structural strength of the sewer pipes. WEF-ASCE (1994) recommends checking the effectiveness of the grouting activities five years after the application and periodically thereafter depending on the inspection policy.

4.2.3 Sliplining

Sliplining inserts a continuous pipe or short pipes into existing damaged pipes. In this case, an annulus between the existing pipe and linear pipe should be grouted to provide support for the lining. When continuous pipes are used, the pipe segments are joined on the ground and then inserted through lead-in trench. The inserted liner pipes are pulled by a winch at the other side of the rehabilitated segment as shown in Figure 4.4. For pipes longer than 24-inch (600 mm) in diameter, the pipes are joined in the insertion trench due to the limitation of the flexibility of the thick walled pipes.

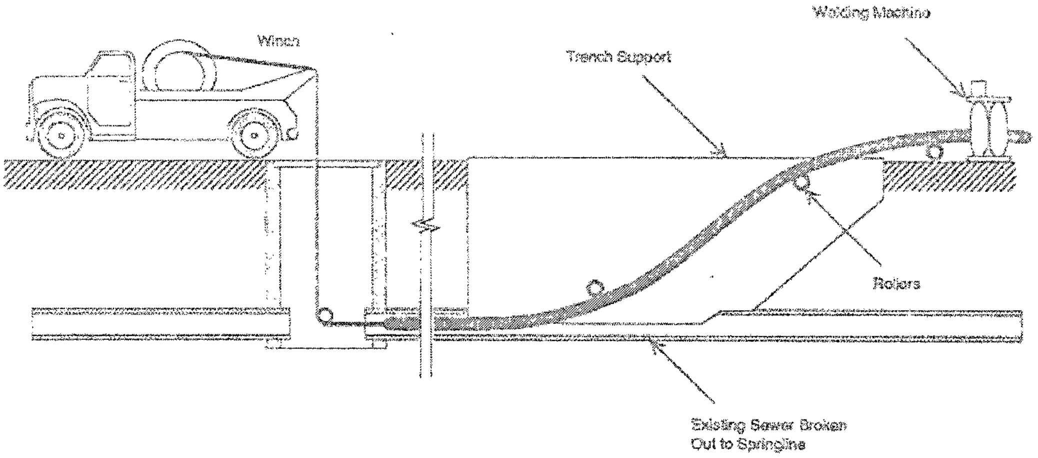
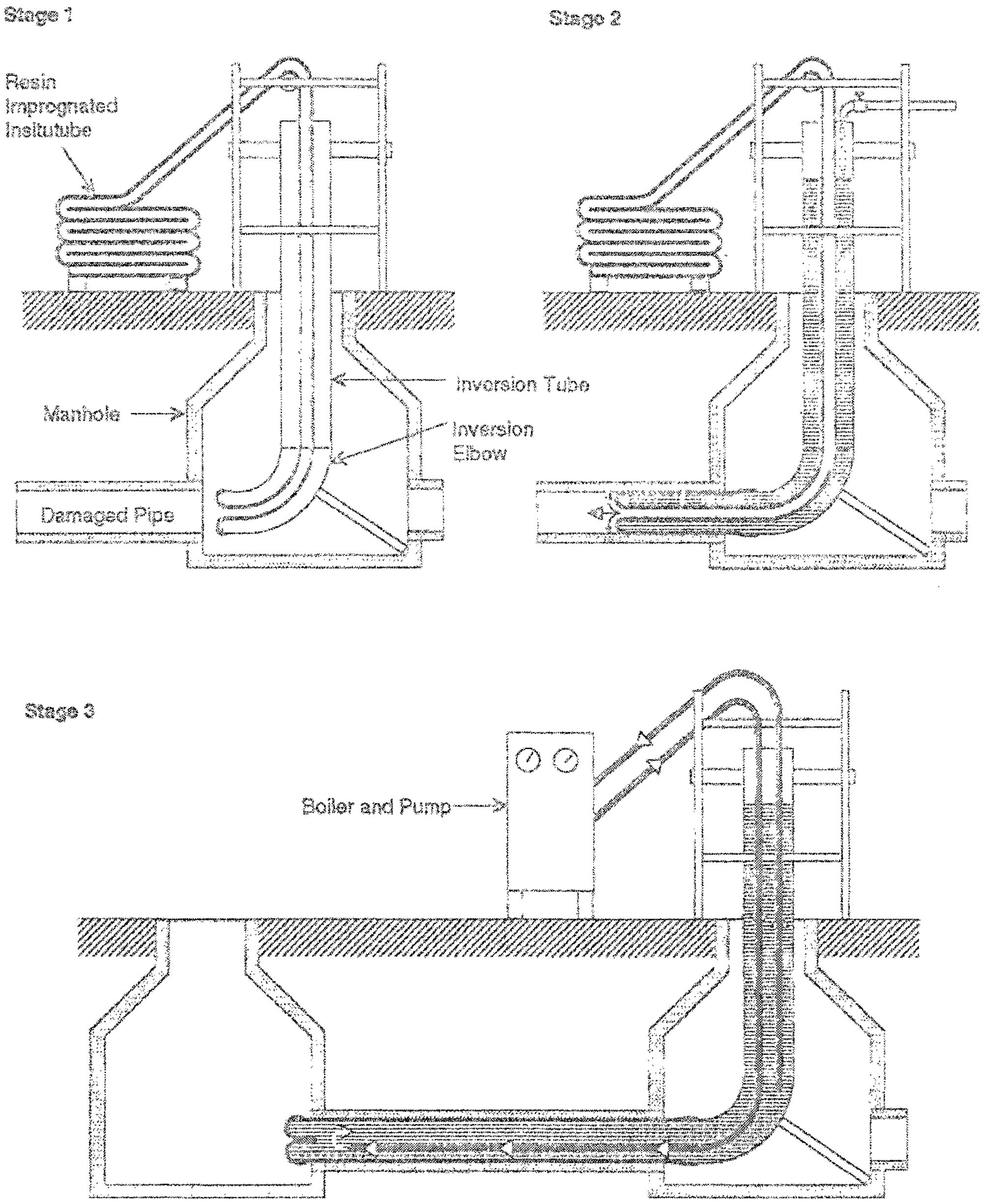


Figure 4.4: Sliplining (WEF-ASCE 1994)

4.2.4 Cured-In-Place Pipe (CIPP) Lining

CIPP lining uses flexible lining for the rehabilitation of the damaged sewer pipes. The liner pipes are inserted from one manhole to the manhole at the other side by winching or inversion process as shown at stage 2 in Figure 4.5.



Courtesy of Insituform™ of North America

Figure 4.5: Cured-in-place pipe lining (WEF-ASCE 1994)

Depending upon the inversion method, CIPP lining is characterized by one of three methods: water inversion, winch inversion, or air inversion. Water inversion applies high-pressured water to invert the liner pipe and uses circulating hot water for cure.

Winched inversion uses the same methods as water inversion for inversion and cure, except that a winch is used for the insertion of the liner pipes. Air inversion uses air for inversion and applies the introducing steam for cure. Since CIPP lining uses flexible liners, this method can be applied to the pipes with slight deformations. Typically, CIPP liners fit closely to the existing pipes, so grouting for the annulus is not required.

4.2.5 Pipe Bursting

Pipe bursting is one of the trenchless technologies that can be employed for the replacement of existing sewer pipes. However, other trenchless technologies such as auger boring, horizontal directional drilling, and pipe ramming are used more often for the installation of new pipelines. When pipe bursting is used, a bursting head (or burster) is inserted into the existing pipes, and then it is pulled by a winch and pushed by a pushing machine as shown in Figure 4.6.

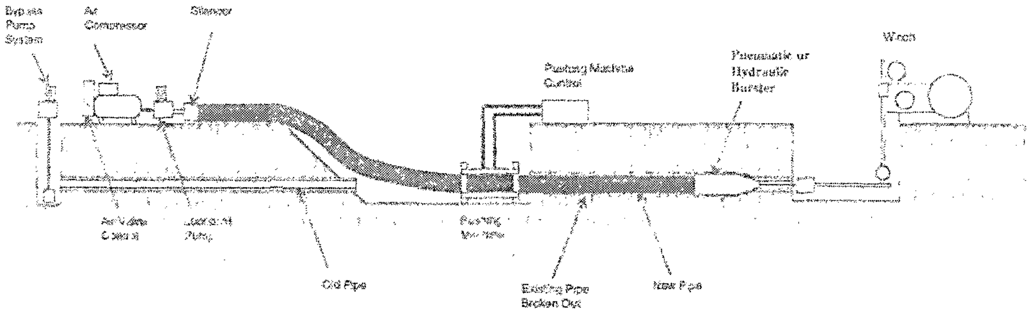


Figure 4.6: Pipe bursting layout (WEF-ASCE 1994)

New pipes are attached to the bursting head and towed along as the bursting head proceeds. The bursting head is operated by pneumatic or hydraulic power to expand the knuckles around the conical shape bursting head. By repeating the bursting and pulling with the winch, the existing pipes are broken into fragments and pushed out to the surrounding ground.

As a trenchless method, pipe bursting provides advantages over the conventional open-cut replacement method. Pipe bursting usually requires less time for construction and reduces the damages to existing facilities such as pavements and buried utilities. It also causes less traffic disruption. However, pipe bursting has application limitations. It presently cannot be used for the replacement of large-size pipes, and its performance substantially depends on the types of surrounding soils. Pipe bursting is only applicable for existing pipes of brittle materials such as vitrified clay, unreinforced concrete, PVC, and cast iron and is not appropriate for the replacement of existing steel, ductile iron, reinforced concrete, and PE pipes.

Open-cut replacement has been the common solution for the improvement of existing sewer pipes. However, in highly congested urban areas or where sewer pipes are installed deep in the ground, trenchless technologies, including pipe bursting, have become a more viable alternative.

4.3 Deteriorated Asset Values Using M & R Alternatives

This section addresses the procedures for the selection of the feasible M & R alternatives for wastewater infrastructure assets based on probabilistic dynamic programming (or MDPs) and the estimation of the asset values using the recommended M & R activities.

4.3.1. Inputs for Dynamic Programming

Let us suppose the following information for dynamic programming regarding the selection of M & R alternatives for wastewater infrastructure assets:

- State space: possible condition states

  $S = \{i \mid 1, 2, 3, 4, 5\}$

  where, 1 = the best condition state

  5 = the worst condition state

- Decision set: possible M & R alternatives (Table 4.1)

Table 4.1: Possible M & R alternatives for wastewater infrastructure assets

a	M & R alternative	Acronym	Type
1	No action	NA	-
2	Routine cleaning	RC	Maintenance
3	Grouting	GR	Preservation
4	Cured-in-place pipe (CIPP) lining	CIPP	Improvement
5	Sliplining	SL	Improvement
6	Pipe bursting	PB	Improvement
7	Open-cut replacement	OR	Improvement

The feasibility of each M & R alternative is determined based on these policies:

- The minimum acceptable condition level of the asset is condition state 4. Thus, the pipes that are in condition states 4 and 5 should be rehabilitated or replaced.
- The alternatives of "no action" and routine cleaning can only be applied for condition states 1 and 2.
- Grouting can upgrade the condition state one level high. However, grouting cannot be applied for the pipes with condition states 4 and 5.
- CIPP lining and sliplining can restore the conditions of the pipes to the initial condition. However, these alternatives are not appropriate for the pipes in condition state 5.
- Pipe bursting and open-cut replacement can be used for the pipes with condition rating 5. After the pipe bursting or open-cut replacement activities are performed, the condition of the pipes returns to the initial condition (condition state 1).
- The alternatives that cover the worse conditions can be applied to the pipes with better conditions, because the pipe conditions are improved more when these alternatives are applied, given that they cost less. For instance, if pipe bursting is less expensive than grouting, then it can be applied for the pipes in condition state 3, although grouting is the typical solution for these pipes.

Based on the feasibility, the applicability of M & R alternatives can be tabulated as shown in Table 4.2.

Table 4.2: Applicability of M & R alternatives

Condition State (i)	M & R Alternatives (a)						
	NA	RC	GR	CIPP	SL	PB	OR
1	Y	Y	Y	Y	Y	Y	Y
2	Y	Y	Y	Y	Y	Y	Y
3			Y	Y	Y	Y	Y
4				Y	Y	Y	Y
5						Y	Y

- Transition probability

Let us suppose that transition probability is as given in equation (4.11) for this illustrative example. Assuming that this transition matrix is obtained from deterioration modeling using condition rating data with no application of preservation or improvement activities, it can be used for the computation of minimum expected costs for "no action" and routine cleaning alternatives.

$$P = \begin{bmatrix} 0.95 & 0.05 & 0 & 0 & 0 \\ 0 & 0.90 & 0.10 & 0 & 0 \\ 0 & 0 & 0.80 & 0.20 & 0 \\ 0 & 0 & 0 & 0.60 & 0.40 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{4.11}$$

The transition matrix for preservation activities (grouting is regarded as a preservation activity among the M & R alternatives) can be obtained by shifting the probabilities in equation (4.11). In this study, the method given by equation (4.3) is used as the transition matrix for the grouting option as shown in equation (4.12).

$$P = \begin{bmatrix} 0.95 & 0.05 & 0 & 0 & 0 \\ 0.95 & 0.05 & 0 & 0 & 0 \\ 0 & 0.90 & 0.10 & 0 & 0 \\ 0 & 0 & 0.80 & 0.20 & 0 \\ 0 & 0 & 0 & 0.60 & 0.40 \end{bmatrix} \tag{4.12}$$

For CIPP lining, sliplining, pipe bursting, and open-cut replacement, it is assumed that the condition states of the pipes return to the initial condition after these activities are performed. Thus, the equation (4.7) can be used as the transition matrix for these M & R alternatives.

- Expected costs

The expected costs for M & R activities are the required expenditures when a sewer pipe is in condition state *i* and an alternative *a* is selected during stage *n*. The costs for the considered M & R alternatives vary, depending only on the selected alternative, regardless of the condition state *i* or stage *n* of the process. The costs for the M & R alternatives are assumed for this example and tabulated as shown in Table 4.3.

Table 4.3: Costs for M & R alternatives (example)

Condition State (*i*)	Costs for M & R Alternatives (*a*) ($/LF)						
	NA	RC	GR	CIPP	SL	PB	OR
1	0	5	10	15	20	25	30
2	0	5	10	15	20	25	30
3			10	15	20	25	30
4				15	20	25	30
5						25	30

4.3.2 Optimization Based on Dynamic Programming

As mentioned in Section 4.1.3, three methods are available for the determination of an optimal policy for the dynamic programming problem. Among the three methods, the value iteration method is used for the optimization process in this study. When using the value iteration method, the equation (4.10) for the dynamic programming problem can be expressed as shown in equation (4.13).

$$f_n(i) = \min_a \{C_n(i,a) + \alpha \sum_{j=1}^{5} p(j \mid i,a,n) f_{n-1}(i)\}$$
$$f_0(i) = 0 \tag{4.13}$$

where, $f_0(i)$ = minimum expected costs for the end of the problem

When using equation (4.13), the stage number (iteration number) n implies the number of stages included in the analysis from the end of the problem. For instance, if a horizon length of 30 years is used for the analysis, the stage numbers, n, are 0, 1, 2, ..., 30, for year 30, 29, 28, ..., 0 respectively. For the simplicity of the computations, the discount factor, α, is assumed to be 1. The expected costs for the alternatives that are not feasible for some condition states have an arbitrary large number so that the alternatives are not selected during the value iteration processes. In the following paragraphs the procedures to compute the minimum expected costs for several stages are presented.

Iteration 1.

$$f_1(i) = \min_a \{C_n(i,a)\} \tag{4.14}$$

Since the initial minimum expected cost is zero, the second term of the equation (4.13) becomes zero, resulting in the minimum expected cost for each condition state being equal to the costs given alternative a. The results of the value iteration process for iteration 1 are summarized in Table 4.4.

Table 4.4: Results of value iteration 1 (example)

Condition State (i)	$f_n(i)=\min_a\{C_n(i,a)+\alpha\sum_{j=1}^{5}p(j\mid i,a,n)f_{n-1}(i)\}$							$f_1(i)$	a
	NA	RC	GR	CIPP	SL	PB	OR		
1	\$0	\$5	\$10	\$15	\$20	\$25	\$30	\$0	NA
2	\$0	\$5	\$10	\$15	\$20	\$25	\$30	\$0	NA
3			\$10	\$15	\$20	\$25	\$30	\$10	GR
4				\$15	\$20	\$25	\$30	\$15	CIPP
5						\$25	\$30	\$25	PB

Iteration 2.

$$f_2(i)=\min_a\{C_2(i,a)+\alpha\sum_{j=1}^{5}p(j\mid i,a,2)f_1(i)\} \tag{4.15}$$

In equation (4.15), $C_2(i, a)$ has the same costs as shown in Table 4.3. Thus, by adding the expected discounted costs during the period 1, $\alpha\sum_{j=1}^{5}p(j\mid i,a,2)f_1(i)$, to the expected cost, $C_2(i, a)$, the expected cost for each alternative can be computed as follows:

(1) $i = 1$, a = no action (transition matrix given in equation (4.11))

$$\{C_2(i,a)+\alpha\sum_{j=1}^{5}p(j\mid i,a,2)f_1(i)\} = 0 + 0.95\text{x}0 + 0.05\text{x}0 + 0\text{x}10 + 0\text{x}15 + 0\text{x}25 = 0$$

(2) $i = 1$, a = routine cleaning (transition matrix given in equation (4.11))

$$\{C_2(i,a)+\alpha\sum_{j=1}^{5}p(j\mid i,a,2)f_1(i)\} = 5 + 0.95\text{x}0 + 0.05\text{x}0 + 0\text{x}10 + 0\text{x}15 + 0\text{x}25 = 5$$

(3) $i = 1$, a = grouting (transition matrix given in equation (4.12))

$$\{C_2(i,a)+\alpha\sum_{j=1}^{5}p(j\mid i,a,2)f_1(i)\} =10 + 0.95\text{x}0 + 0.05\text{x}0 + 0\text{x}10 + 0\text{x}15 + 0\text{x}25=10$$

(4) $i = 1$, a = CIPP lining (transition matrix given in equation (4.7))

$$\{C_2(i,a)+\alpha\sum_{j=1}^{5}p(j\mid i,a,2)f_1(i)\} = 15 + 1\text{x}0 + 0\text{x}0 + 0\text{x}10 + 0\text{x}15 + 0\text{x}25 = 15$$

(5) $i = 1$, a = sliplining (transition matrix given in equation (4.7))

$$\{C_2(i,a)+\alpha\sum_{j=1}^{5}p(j\mid i,a,2)f_1(i)\} = 20 + 1\text{x}0 + 0\text{x}0 + 0\text{x}10 + 0\text{x}15 + 0\text{x}25 = 20$$

(6) $i = 1$, a = pipe bursting (transition matrix given in equation (4.7))

$$\{C_2(i,a)+\alpha\sum_{j=1}^{5}p(j\,|\,i,a,2)f_1(i)\} = 25 + 1\text{x}0 + 0\text{x}0 + 0\text{x}10 + 0\text{x}15 + 0\text{x}25 = 25$$

(7) $i = 1$, a = open-cut replacement (transition matrix given in equation (4.7))

$$\{C_2(i,a)+\alpha\sum_{j=1}^{5}p(j\,|\,i,a,2)f_1(i)\} = 30 + 1\text{x}0 + 0\text{x}0 + 0\text{x}10 + 0\text{x}15 + 0\text{x}25 = 30$$

For other j's, the same procedure can be used for the computations. However, as j changes to 2, 3, 4, and 5, the probability values required for the computation should be extracted from the corresponding row of the transition matrix related to the M & R alternatives. The results of iteration 2 are listed in Table 4.5.

Table 4.5: Results of value iteration 2 (example)

Condition State (i)	$f_n(i)=\min_a\{C_n(i,a)+\alpha\sum_{j=1}^{5}p(j\,|\,i,a,n)f_{n-1}(i)\}$							$f_2(i)$	a
	NA	RC	GR	CIPP	SL	PB	OR		
1	$0	$5	$10	$15	$20	$25	$30	$0	NA
2	$1	$6	$10	$15	$20	$25	$30	$1	NA
3			$11	$15	$20	$25	$30	$11	GR
4				$15	$20	$25	$30	$15	CIPP
5						$25	$30	$25	PB

The same procedure is applied to find the optimal policy for M & R of wastewater infrastructure assets. It can be seen in Table 4.6 that given the inputs and assumptions, the optimal M & R alternative for each condition state changes at iteration 12 and iteration 31.

Table 4.6: Optimal M & R alternatives (example)

Condition State (i)	Analysis Period		
	1-11 years	12-30 years	≥ 31 years
1	No action	No action	Routine cleaning
2	No action	No action	Grouting
3	Grouting	CIPP lining	CIPP lining
4	CIPP lining	CIPP lining	CIPP lining
5	Pipe bursting	Pipe bursting	Pipe bursting

The results shown in Tables 4.4, 4.5, and 4.6 indicate that the optimal alternatives change as the length of the planning horizon varies. For instance, if the budget planning period is less than 12 years, "no action" is the optimal alternative for condition states 1 and 2, while grouting, CIPP lining, and pipe bursting are the optimal alternatives for condition states 3, 4, and 5 respectively. On the other hand, if the planning horizon is between 12 and 30 years, the optimal M & R alternatives for condition states 1, 2, 3, 4, and 5 are "no action," "no action," CIPP lining, CIPP lining, and pipe bursting respectively. Routine cleaning, grouting, CIPP lining, CIPP lining, and pipe bursting are the optimal alternatives for condition states 1, 2, 3, 4, and 5 respectively, for the planning horizon of more than 30 years.

The results of the optimization using the dynamic programming emphasize the importance of preventive maintenance. For instance, for pipe segments in condition state 3, the optimization results recommend the use of CIPP lining rather than grouting since CIPP lining is more cost-effective than grouting in the long term. For pipe segments in condition state 1, routine maintenance is recommended rather than "no action" in the long run. Therefore, the LCCA recommends applying M & R alternatives that increase the functionality of wastewater infrastructure assets after all even though they cost more in early stages of the investment horizon.

4.3.3 Deteriorated Value Using the Optimal M & R Alternatives

In this section, the procedures are discussed for the estimation of the values of wastewater infrastructure assets using the valuation methods described in Chapter 3 and the optimal M & R alternatives are selected based on dynamic programming. For illustration purposes, five segments are assumed and the priority for M & R is given to the segments in the worst condition states as shown in Table 4.7, which are the condition states of the five pipe segments inspected in 2001.

Table 4.7: Pipe segments for analysis (example)

Pipe ID	Length (ft)	Installation year	Rating
1	100	1965	5
2	100	1971	4
3	100	1982	3
4	100	1992	2
5	100	1994	1
Total	500		

4.3.3.1 Procedures for the Computation of Deteriorated Value

When the values of wastewater infrastructure assets are estimated based on the deteriorated value method, several aspects have to be considered regarding the M & R activities applied and the present condition states of the pipe segments. The condition rating is changed every year due to the deterioration of the assets. These condition ratings can be obtained from the deterioration curve using the assumed transition matrix. If pipe segments receive improvement treatment (CIPP lining or pipe bursting) or preservation treatment (grouting), the condition state changes to condition 1 for CIPP lining and pipe bursting or condition state 2 for grouting.

The *expected total added value* (ETAV) obtained from the investments on M & R activities for the first transition can be calculated using equation (4.16).

$$v_i = \sum_j p_{ij} c_{ij} \qquad (4.16)$$

where, v_i = expected added value

p_{ij} = transition probability

c_{ij} = transition costs associated with transition probabilities

In using equation (4.16) for the computation of ETAV, the transition matrix given in equation (4.7) can be used for CIPP lining and pipe bursting alternatives, and transition matrix in equation (4.12) can be used for grouting option. In the cost matrix, only the cells of c_{32}, c_{41}, and c_{51} have non-zero values when the grouting, CIPP lining, and pipe bursting alternatives are applied. This corresponds to the assumptions for the feasibility of M & R alternatives. For instance, if grouting is applied for the segment in condition state 3, the cost is \$1,000 (100 ft x \$10/ft). Hence, the ETAV for this case is

$$v_i = \sum_j p_{ij} c_{ij}$$

$$= \begin{bmatrix} 0.95 & 0.05 & 0 & 0 & 0 \\ 0.95 & 0.05 & 0 & 0 & 0 \\ 0 & 0.90 & 0.10 & 0 & 0 \\ 0 & 0 & 0.80 & 0.20 & 0 \\ 0 & 0 & 0 & 0.60 & 0.40 \end{bmatrix} \begin{bmatrix} \$0 & \$0 & \$0 & \$0 & \$0 \\ \$0 & \$0 & \$0 & \$0 & \$0 \\ \$0 & \$1{,}000 & \$0 & \$0 & \$0 \\ \$0 & \$0 & \$0 & \$0 & \$0 \\ \$0 & \$0 & \$0 & \$0 & \$0 \end{bmatrix}$$

$$= 0.90 \times \$1{,}000 = \$900$$

When M & R activities are performed over more than one year, the deteriorated values (DVs) are computed using equations (3.19) and (3.24) for base year and year 1. However, the DVs for year 2 and thereafter are estimated using different equations depending upon the condition states and the history of prior M & R treatments. The logic that is used for the derivation of the equations for DV computation is presented in Figures 4.7 and 4.8 for improvement and preservation activities respectively. The related equations for the pipe segments in condition states 4 and 5 based on the history of improvement activities are given in equations (4.17) through (4.19).

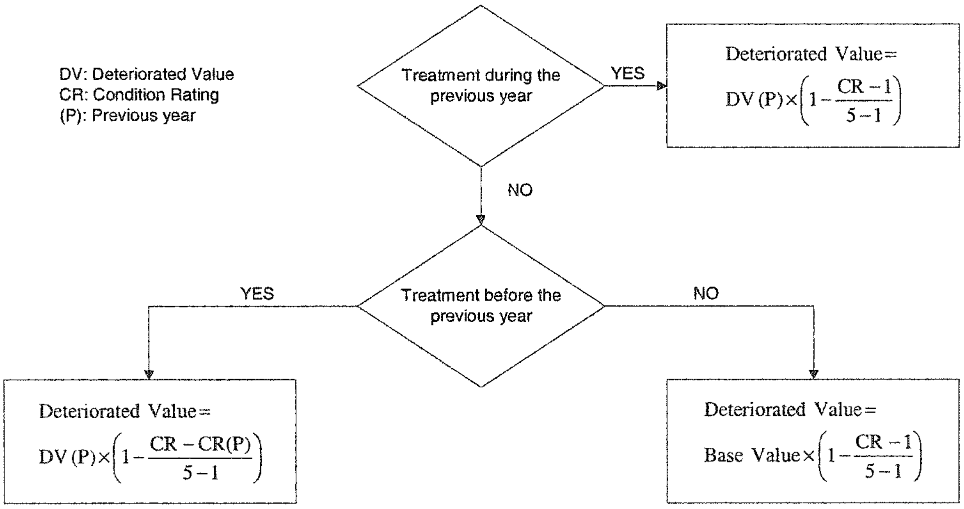


Figure 4.7: Logic for the computation of deteriorated value (Improvement)

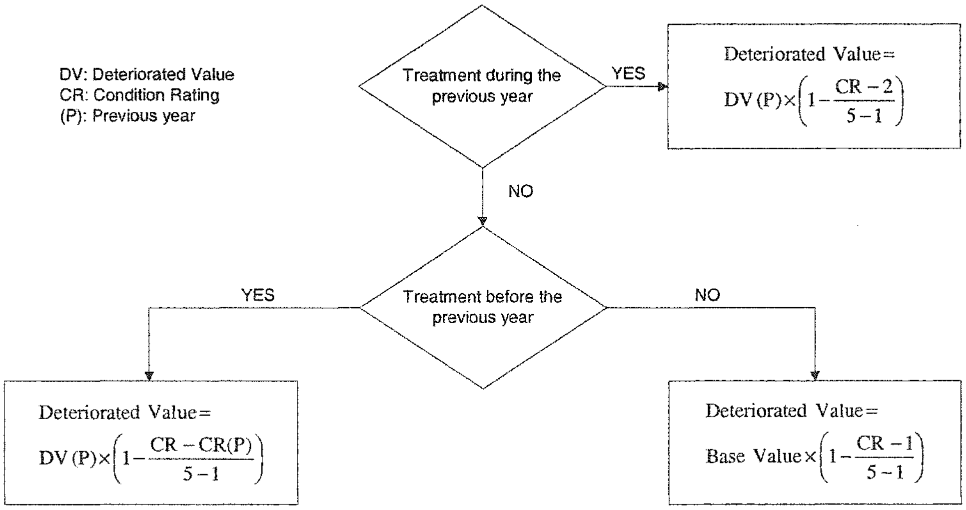


Figure 4.8: Logic for the computation of deteriorated value (Preservation)

- If the pipe receive improvement treatment during the previous year:

$$DV = DV(P) \times \left(1 - \frac{CR - 1}{5 - 1}\right) \tag{4.17}$$

- If the pipe receive improvement treatment before the previous year:

$$DV = DV(P) \times \left(1 - \frac{CR - CR(P)}{5 - 1}\right) \tag{4.18}$$

- If there is no history of improvement treatment:

$$DV = Base\ Value \times \left(1 - \frac{CR - 1}{5 - 1}\right) \tag{4.19}$$

where, DV = deteriorated value

CR = condition rating

(P) = previous year

If a pipe segment was in condition state 4 or 5 and received an improvement treatment (CIPP lining or pipe bursting) during the previous year, the deteriorated value of the current year can be computed using equation (4.17) that includes the deteriorated value of the previous year and the condition changes from the initial condition (condition state 1). If the segment received an improvement treatment before the previous year, the condition of the segment has been changed from condition state 1 due to deterioration. Therefore, the difference between the conditions of the previous year and the current year is used for the computation of deteriorated value as shown in equation (4.18). If the segment has never received any improvement treatment, the deteriorated value can be estimated using the base value and the current condition as shown in equation (4.19).

The same logic can be used for the pipe segments in condition state 3 except for the case of receiving a preservation treatment during the previous year. Since it is assumed that the preservation treatment upgrades the condition of a pipe segment from condition 3 to condition 2, the deteriorated value for this case uses the difference between the current condition and condition state 2 as shown in equation (4.20). For other cases, equation (4.18) and (4.19) can be used.

$$DV = DV(P) \times \left(1 - \frac{CR-2}{5-1}\right) \tag{4.20}$$

For the pipe segments in condition states 1 and 2, for which routine cleaning is applied, the equation (4.21) can be used for the computation of deteriorated values. Since routine cleaning does not improve the conditions of the sewer pipes, one equation can be used for the computation.

$$DV = DV(P) \times \left(1 - \frac{CR-CR(P)}{5-1}\right) \tag{4.21}$$

4.3.3.2 Computation of Infrastructure Asset Values

The asset values for the base year (Year 0) using three valuation methods, i.e., the deteriorated value (DV) method, the depreciation method (or Book value), and the modified approach, are estimated and presented in Table 4.8.

Table 4.8: Asset values for base year (example)

No.	Length	Year	Rating	Base Value	Deteriorated Value	Book Value	Modified Approach
1	100	1965	5	$459	$0	$201	$459
2	100	1971	4	$748	$187	$397	$748
3	100	1982	3	$1,809	$905	$1,272	$1,809
4	100	1992	2	$2,358	$1,769	$2,026	$2,358
5	100	1994	1	$2,558	$2,558	$2,278	$2,558
	500			$7,933	$5,418	$6,175	$7,933
					100%	114%	146%

In Table 4.8, the base value is estimated using the open-cut replacement cost adjusted for inflation based on the Engineering News Record Construction Cost Index (ENR CCI) and the installation year. For example, for pipe segment 1, the replacement cost before the adjustment is $30/ft x 100 ft = $3,000. Since the ENR CCIs are 971 and 6,342 for year 1965 and 2001 respectively, the adjusted replacement cost (base value) can be obtained by dividing $3,000 by the adjustment factor, which is 971 divided by 6,342, resulting in $459.

The asset values using the depreciation method can be estimated by subtracting the loss in value due to depreciation from the asset value of the previous year. In this example, salvage value is assumed to be $0. The expected useful life estimated using the transition matrix given in equation (4.11) is 64 years. From Table 4.8 it can be observed that the estimated book value is 14% higher than the deteriorated value.

The asset values using the modified approach are the same as the base values since the modified approach does not take consideration of depreciation or deterioration in the valuation process. The deteriorated value is computed using equation (3.19) to reflect the deterioration of the wastewater infrastructure assets. Therefore, the modified approach-based value is 46% higher than the deteriorated value.

Using the optimal M & R alternatives obtained from the dynamic programming process, the changes in asset value due to M & R activities over time can be investigated. Suppose the pipe segments given in Table 4.7 are repaired over the next three years. The optimal alternatives for condition states 1, 2, 3, 4, and 5 are "no action," "no action," grouting, CIPP lining, and pipe bursting respectively. The required budget for M & R of the given pipe segments is $5,000, of which $2,500 is for the segment with condition 5, $1,500 is for the segment with condition 4, and $1,000 is for the pipe with condition 3. If this required budget is allocated evenly over the next three years, $1,667 is available for M & R each year. Based on the available budget of $1,667 per year, the asset values of the pipe segments can be estimated based on the assumption that if the entire budget allocated for a year is not expended during that year, the remainder of the budget is moved over to the next year.

The estimated values for the given example using the three valuation methods for a three-year investment are summarized in Tables 4.9, 4.10, and 4.11. There are differences, as shown in these tables, between the asset values depending on the valuation method used, particularly when the deterioration of the asset is reflected in the asset values.

In year 1, the pipe segment 2 is repaired using the CIPP lining since the pipe segment 1 requires more investment than the available fund (Table 4.9). Therefore, the amount of $1,500 is added to the three asset values. In year 2, the segment 3 is repaired using grouting since the available fund of $1,833 including $167 which is carried over from year 1 is not sufficient for the pipe segment 1 to receive pipe bursting treatment (Table 4.10). The cost for grouting is added to the deteriorated value and the book value, while the modified approach-based value does not change. The pipe segment 1 is rehabilitated using pipe bursting in year 3 and the cost for pipe bursting is added to the three asset values (Table 4.11).

The book values for three years can be calculated by subtracting the amount of depreciation using the straight-line method from the book value of the previous year. The modified approach estimates the asset values without depreciation. Thus, asset values remain the same unless improvement activities (CIPP lining or pipe bursting in this example) are performed.

Table 4.9: Asset values in year 1 (example)

Year 1 Available Fund = $1,667

(1) No.	(2) Length (ft)	(3) Year	(4) M & R Alternative	(5) Unit Cost ($/LF)	(5) M & R Cost	(7) Base Value	(8) Rating	(9) Deteriorated Value	(10) Expected Added Value	(11) Deteriorated Value =(9)+(10)	(12) Book Value	(13) Modified Approach
1	100	1965	Pipe Bursting	$25	$0	$459	5	$0	$0	$0	$194	$459
2	100	1971	CIPP lining	$15	$1,500	$748	4.06	$176	$1,500	$1,676	$1,886	$2,248
3	100	1982	Grouting	$10	$0	$1,809	3.07	$873	$0	$873	$1,244	$1,809
4	100	1992	No Action	$0	$0	$2,358	2.09	$1,716	$0	$1,716	$1,990	$2,358
5	100	1994	No Action	$0	$0	$2,558	1.05	$2,526	$0	$2,526	$2,238	$2,558
	500				$1,500	$7,933		$5,290		$6,790	$7,551	$9,433
										100%	111%	139%

Table 4.10: Asset values in year 2 (example)

Year 2 Available Fund = $1,833

(1) No.	(2) Length (ft)	(3) Year	(4) M & R Alternative	(5) Unit Cost ($/LF)	(5) M & R Cost	(7) Base Value	(8) Rating	(9) Deteriorated Value	(10) Expected Added Value	(11) Deteriorated Value =(9)+(10)	(12) Book Value	(13) Modified Approach
1	100	1965	Pipe Bursting	$25	$0	$459	5	$0	$0	$0	$187	$459
2	100	1971	No Action	$0	$0	$748	1.05	$1,655	$0	$1,655	$1,874	$2,248
3	100	1982	Grouting	$10	$1,000	$1,809	3.15	$837	$900	$1,737	$2,216	$1,809
4	100	1992	No Action	$0	$0	$2,358	2.19	$1,673	$0	$1,673	$1,953	$2,358
5	100	1994	No Action	$0	$0	$2,558	1.10	$2,495	$0	$2,495	$2,198	$2,558
	500				$1,000	$7,933		$6,659		$7,559	$8,427	$9,433
										100%	111%	125%

Table 4.11: Asset values in year 3 (example)

Year 3 Available Fund = $2,500

(1) No.	(2) Length (ft)	(3) Year	(4) M & R Alternative	(5) Unit Cost ($/LF)	(6) M & R Cost	(7) Base Value	(8) Rating	(9) Deteriorated Value	(10) Expected Added Value	(11) Deteriorated Value =(9)+(10)	(12) Book Value	(13) Modified Approach
1	100	1965	Pipe Bursting	$25	$2,500	$459	5	$0	$2,500	$2,500	$2,679	$2,959
2	100	1971	No Action	$0	$0	$748	1.1	$1,634	$0	$1,634	$1,862	$2,248
3	100	1982	No Action	$0	$0	$1,809	2.09	$1,698	$0	$1,698	$2,187	$1,809
4	100	1992	No Action	$0	$0	$2,358	2.28	$1,635	$0	$1,635	$1,916	$2,358
5	100	1994	No Action	$0	$0	$2,558	1.16	$2,457	$0	$2,457	$2,158	$2,558
	500				$2,500	$7,933		$7,424		$9,924	$10,803	$11,933
										100%	109%	120%

The deteriorated values can be calculated using the procedures and equations described in Section 4.3.3.1. For instance, the deteriorated value in column (9) in Table 4.9 can be computed using equation (4.19) considering the condition changes given in column (8). The expected total added value given in column (10) is calculated using equation (4.16) and then added to the deteriorated value in column (9) resulting in the deteriorated value in column (11) representing the deteriorated value after treatments.

The deteriorated values given in column (9) in Tables 4.10 and 4.11 are calculated using one of the equations given in equation (4.17) through (4.21). For instance, the deteriorated value of the pipe segment 2 in year 2 is computed using equation (4.17) (Table 4.10).

The results indicate that there are certain factors that affect the values of wastewater infrastructure assets for each valuation method. The investment for M & R is a common factor that influences the asset values, even though the level of impact is different among the valuation methods, depending on how the investment is recorded in the financial report of the municipalities. The depreciation method is age-sensitive. The rate of depreciation depends on the value for expected useful life and the age of the assets in the computation. The asset values estimated using the deteriorated value method are affected by the condition states of the assets. In this case, the asset values do not depend on the age of the assets but rather on the assets' condition. On the other hand, the modified approach is affected by neither age nor condition states of the assets. Thus, there is no loss in asset value when the modified approach is used for the valuation of infrastructure assets. Only gains can be observed in asset value when improvement activities such as rehabilitation and replacement activities are performed and the modified approach is used for valuation process.

4.4 Chapter Summary

This chapter presented an overview of the dynamic programming technique that is used for the selection of optimal M & R alternatives for wastewater infrastructure assets. The compositions of transition probabilities for different types of M & R activities were also presented in this chapter. A set of sample pipe segments was used to explain the LCCA for M & R activities using the optimization process based on the dynamic programming. Using the results of LCCA, the methods for the estimation of infrastructure asset values were addressed. The details of procedures for the estimation of deteriorated value and computation results for the sample pipe segments were described.

CHAPTER 5. IMPLEMENTATION AND VALIDATION OF THE DETERIORATION-BASED VALUATION MODEL

This chapter presents the implementation and validation of the deterioration-based valuation model using the actual wastewater infrastructure assets in the City of San Diego. A Markov chain-based deterioration model is developed using the condition data obtained from the City of San Diego. For the estimation of transition probability for the Markov chain-based deterioration model, two methods are applied: the nonlinear optimization-based approach and the ordered probit model-based approach, which were presented in Chapter 3. The deterioration-based valuation model is then used for the estimation of the values of wastewater infrastructure assets using the procedures described in Chapter 4. This chapter concludes with a comparison of the changes in asset values of different maintenance activities using different valuation methods.

5.1 Descriptions for Data

The data sets used for the development of the deterioration models and the valuation of wastewater infrastructure assets in this study are described in this section. This information includes data source, attributes of the data, and the methods of condition assessment of the wastewater infrastructure assets used.

5.1.1 Data Acquisition

The City of San Diego's Metropolitan Wastewater Department (MWWD) manages approximately 3,000 miles (4,800 km) of sanitary sewer lines. As a part of a 10-year capital program of pipe replacement and rehabilitation, MWWD is conducting an inspection program to evaluate the conditions of the sewer pipes. The data used in this paper was obtained from the inspections of phase 1A, wherein approximately 55 miles (90 km) of sewer pipes were inspected during the latter half of 2001 as shown in Figure 5.1 (San Diego 2002). The attributes of the inspected pipes are summarized in Table 5.1.

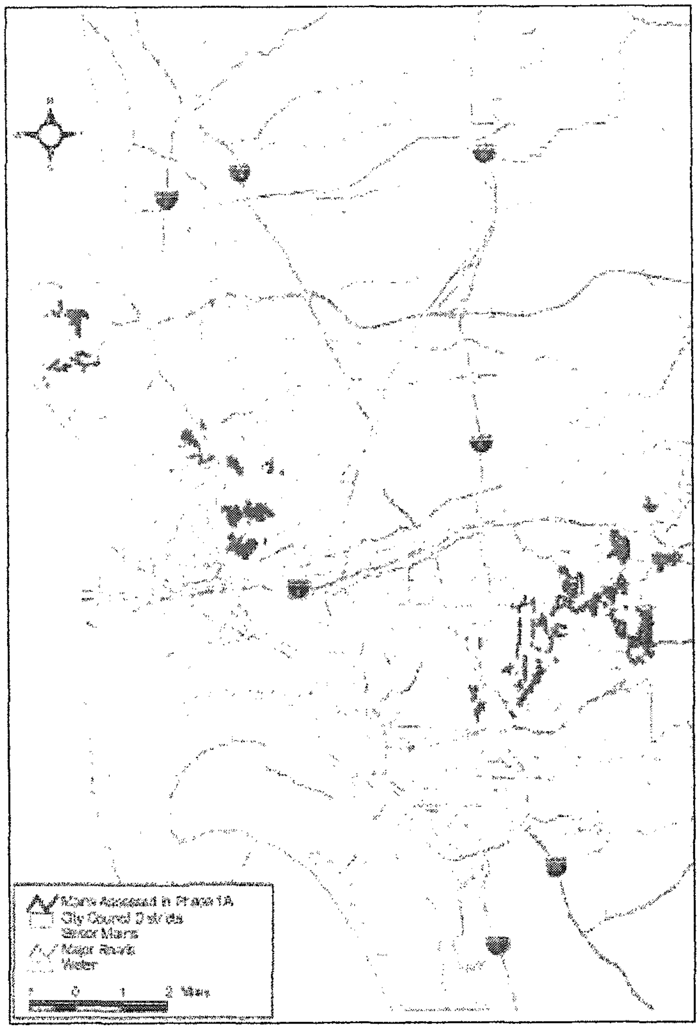


Figure 5.1: Sewer pipes assessed in CCTV phase (San Diego 2002)

Table 5.1: Attributes of the wastewater infrastructure assets of the City of San Diego

Attributes		Miles (km)	Percent
Age (Installation Date)	Before 1951	21.9 (13.7)	39%
	1952 – 1965	28.1 (17.6)	51%
	After 1965	5.4 (3.4)	10%
	Total	55.4 (34.6)	100%
Diameter	6 inches (150 mm)	12.8 (8.0)	23%
	8 inches (200 mm)	39.2 (24.5)	71%
	10 inches (250 mm)	2.5 (1.6)	5%
	12 inches (300 mm)	0.7 (0.4)	1%
	15 inches (375 mm)	0.1 (0.1)	0%
	21 inches (525 mm)	0.1 (0.1)	0%
	Total	55.4 (34.6)	100%
Material	Vitrified Clay (VC)	50.5 (31.6)	91%
	Polyvinyl Chloride (PVC)	3.7 (2.3)	7%
	Concrete (CP)	0.6 (0.4)	1%
	Others	0.6 (0.4)	1%
	Total	55.4 (34.6)	100%

As shown in Table 5.1, most of the sewer pipes are vitrified clay (VC) and polyvinyl chloride (PVC) with sizes ranging from 6 to 10 inches (150 to 250 mm) in diameter. About 90% of the pipes were installed before 1965, and 94% of the pipes were 8 inches or smaller in diameter.

5.1.2 Condition Assessment

The condition rating system used for the inspection consists of 108 criteria. The entire rating system is composed of seven sub-groups: structural defects, cracks, infiltration, lateral connections, debris and grease, roots, and others. Each sub-group contains rating criteria describing both the characteristics and the severity of the defects. For each criterion, maintenance and/or structural points are assigned to evaluate the condition of the sewer pipes. Samples of the criteria and assigned points are presented in Table 5.2.

Table 5.2: Samples of standard defect codes and point values for San Diego MWWD

Code and Severity	Observation	Description	Maintenance Points	Structural Points
D – S	Deformation, Small	Less than 15% of inside diameter	0	50
D – M	Deformation, Medium	Between 15% and 30% of inside diameter	0	100
D – L	Deformation, Large	> 30%	0	150
X – N	Collapsed Pipe	Use if a section of the pipe wall has fallen in and the structural integrity of pipe has been compromised.	0	700
DEG – S	Debris – Grease, Small	Slight indication 0.25 inch (6.25 mm) to 0.5 inch (12.5 mm) thick	50	0
DEG – M	Debris – Grease, Medium	0.5 inch (12.5 mm) to 2 inch (50 mm) thick	75	0
DEG – L	Debris – Grease, Large	Greater than 2 inch (50 mm) thick	150	0
CRA – S	Roots around Lateral, Small	Small roots from around the outside of the lateral	20	50
CRA – M	Roots around Lateral, Medium	Medium roots from around the outside of the lateral	50	50
CRA – L	Roots around Lateral, Large	Heavy roots from around the outside of the lateral	75	100

Based on the assigned structural and maintenance points from the inspection, the condition ratings are computed using equation (5.1).

$$Score = \frac{\Sigma SP \times SW + \Sigma MP \times MW}{LS} \qquad (5.1)$$

where, SP = structural points

SW = structural weight

MP = maintenance points

MW = maintenance weight

LS = length of segment

The structural weight and the maintenance weight used for the condition rating are 1 and 0, respectively. Once the score for each sewer segment is calculated, the condition of the pipe is designated using one of the letter condition ratings from A to E. For instance, scores in the range of 0 to 2.5 are classified as condition rating A while scores that are greater than 6.0 are classified as condition rating E. In this rating system, condition rating A indicates that the pipe is in the best condition, whereas the condition rating E denotes the worst condition. The ranges used to categorize the conditions of the pipes are given in Table 5.3.

Table 5.3: Score ranges for condition ratings

Condition rating	Score Range
A	0 to 2.5
B	0 to 2.5
C	2.5 to 4.0
D	4.0 to 6.0
E	Above 6.0

In this rating system, pipes with condition rating A and condition rating B have the same score range. Depending on the existence of major defects such as a broken pipe, hole in pipe, deformation, broken joint, etc that can cause relatively severe damage to the pipes, pipe segments are rated as condition A or condition B. If there is at least one major defect in the sewer segment, the segment is rated as condition rating B even though the score is between 0 and 2.5.

5.2 Development of Deterioration Models

In this section the Markov chain-based deterioration models are presented. For the estimation of transition probabilities of the Markov chain model, two methods are applied: the nonlinear optimization-based approach and ordered probit model-based approach.

5.2.1 Nonlinear Optimization-Based Approach

For the development of the Markov chain-based deterioration models, the entire data set was divided into five subsets based on the type of material and size: 6-inch (150 mm) VC pipes, 8-inch (200 mm) VC pipes, 10-inch (250 mm) VC pipes, 8-inch (200 mm) PVC pipes, and 10-inch (250 mm) PVC pipes. To establish the relationship between the condition ratings and the ages of the sewer pipes, regression analyses were performed for the five data subsets. Five different regression models were investigated to determine the best-fit model to the given data set.

Among the 25 regression analyses, only 8-inch (200 mm) PVC pipes were fitted well to simple exponential distribution, as shown in Table 5.4. Simple exponential distribution was also used for the deterioration prediction modeling for combined sewer systems by Wirahadikusumah et al. (2001).

The estimated relationship between the condition ratings ($Y(t)$) and age (t) for 8-inch (200 mm) PVC pipes is presented in equation (5.2).

$$Y(t) = \exp(0.3061 + 0.0217t) \tag{5.2}$$

In this case, however, the effectiveness of the regression model is questionable since only 12 data points were used in the analysis. Therefore, an assumption was made to screen the data sets for the development of deterioration models. As the installation year for sewer pipes were available only after the year 1952, the sewer pipes can be at most 49 years old in year 2001. So it was assumed that the pipe segments that were 40 or more years old and in condition state 1 received preventive treatments after they were installed. If the dates for the application of rehabilitation activities were available, the age of the pipe segments could be recalculated from the dates. However, since the records for the dates of rehabilitation applications were not available, these data points were excluded from the analysis.

Table 5.4: Summary of regression analysis for 8-inch (200 mm) PVC pipes

Coefficient	Value	P-value	Remarks
$Conditoin\ Rating = \beta_0 + \beta_1 AGE + \beta_2 AGE^2$			
R^2	0.962746		High P-values
β_0	1.309610	0.0245	
β_1	0.030241	0.4173	
β_2	0.000481	0.3892	
$Condition\ Rating = \beta_0 + \beta_1 AGE + \beta_2 AGE^2 + \beta_3 AGE^3$			
R^2	0.992908		High R^2 Low P-values Very high intercept Condition rating decreases, increases, and then decreases again
β_0	5.779863	<0.0001	
β_1	-0.507377	0.0006	
β_2	0.020257	0.0003	
β_3	-0.000216	0.0004	
$Condition\ Rating = \exp(\beta_0 + \beta_1 AGE)$			
R^2	0.945027		Good estimate Initial condition rating (1.36)
β_0	0.306134	<0.0001	
β_1	0.021743	<0.0001	
$Condition\ Rating = \exp(\beta_0 + \beta_1 AGE + \beta_2 AGE^2)$			
R^2	0.945287		High P-values
β_0	0.347881	0.1275	
β_1	0.018621	0.2511	
β_2	0.000047	0.8406	
$Condition\ Rating = \exp(\beta_0 + \beta_1 AGE + \beta_2 AGE^2 + \beta_3 AGE^3)$			
R^2	0.990353		Very high intercept (9.7)
β_0	2.272153	0.0001	
β_1	-0.212803	0.0006	
β_2	0.008560	0.0003	
β_3	-0.000093	0.0003	

The regression analyses conducted using the four new data sets (excluding 10-inch (250 mm) PVC pipes) and the five different regression models identified that 8-inch (200 mm) VC pipes are fitted well to simple exponential distribution. The results of the regression analysis for 8-inch (200 mm) VC pipes are summarized in Table 5.5. In this case, the number of data points used in the analysis was 316. The outputs of regression analysis for other data groups are presented in Appendix A.

Table 5.5: Summary of regression analysis for 8-inch (200 mm) VC pipes

Coefficient	Value	P-value	Remarks
$Conditoin\ Rating = \beta_0 + \beta_1 AGE + \beta_2 AGE^2$			
R^2	0.305117		High Intercept
β_0	3.311237	0.0084	
β_1	-0.162187	0.0163	
β_2	0.003461	0.0001	
$Condition\ Rating = \beta_0 + \beta_1 AGE + \beta_2 AGE^2 + \beta_3 AGE^3$			
R^2	0.305344		High intercept (8.8) High P-values
β_0	2.174685	0.5643	
β_1	-0.046694	0.8990	
β_2	-0.000100	0.9929	
β_3	0.000034	0.7494	
$Condition\ Rating = \exp(\beta_0 + \beta_1 AGE)$			
R^2	0.348862		Good estimate
β_0	-0.948883	<0.0001	
β_1	0.044029	<0.0001	
$Condition\ Rating = \exp(\beta_0 + \beta_1 AGE + \beta_2 AGE^2)$			
R^2	0.389649		High Intercept (2.8)
β_0	1.016135	0.0259	
β_1	-0.366734	0.0067	
β_2	0.0014627	<0.0001	
$Condition\ Rating = \exp(\beta_0 + \beta_1 AGE + \beta_2 AGE^2 + \beta_3 AGE^3)$			
R^2	0.389685		High intercept (3.3) High P-values
β_0	1.191824	0.3855	
β_1	-0.084587	0.5275	
β_2	0.002013	0.6209	
β_3	-0.000005	0.8921	

The average condition rating at age *t*, *Y*(*t*), for 8-inch (200 mm) VC pipes can be expressed as shown in equation (5.3) from the regression.

$$Y(t) = \exp(-0.9489 + 0.0440t) \tag{5.3}$$

The regression model given in equation (5.3) formed the basis for the estimation of transition probabilities of the Markov chain-based deterioration model. The regression function was shifted to cross condition rating 1 at age 0. The transitions of the Markov chain model from state *i* to state *j* were represented by a 5x5 transition probability matrix, since the conditions of City of San Diego wastewater infrastructure can be described from condition rating 1 (best condition) to condition rating 5 (worst condition).

One year was used as a transition period. To meet the homogeneity assumption of the Markov chain model, a "zoning" concept was used wherein a six-year term was used for a zone considering the three-year condition assessment period recommended by GASB 34. Therefore, it was assumed that the values of the transition probabilities would not change over six years. To determine the entire deterioration pattern, it was assumed that no improvement activities were performed over the life of the infrastructure assets. Hence, the transition probabilities will have null values where *i* is greater than *j*. It was also assumed that the condition levels of the wastewater infrastructure assets do not drop more than one level in a transition (one year). Thus, the transition probabilities where *j* is greater than (*i+1*) will be zero. The last cell of the matrix is the absorbing state. Thus, the transition probability matrix ***P*** given in equation (3.3) can be expressed as shown in equation (5.4)

$$\mathbf{P} = \begin{bmatrix} p_1 & 1-p_1 & 0 & 0 & 0 \\ 0 & p_2 & 1-p_2 & 0 & 0 \\ 0 & 0 & p_3 & 1-p_3 & 0 \\ 0 & 0 & 0 & p_4 & 1-p_4 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{5.4}$$

The transition probabilities ($p_1, \ldots, p_4$) can be estimated by using nonlinear optimization technique. The objective function given in equation (3.9) minimizes the sum of the absolute difference of the expected values between the regression model and Markov chain model. The expected value, $E(n, P)$ can be estimated using equation (3.10). Thus, for 8-inch (200 mm) VC pipes, the objective function of nonlinear optimization for the first zone can be expressed as equation (5.5).

$$Minimize \left| e^{-0.9489+0.0440\times 1} + 0.61 - [1 \quad 0 \quad 0 \quad 0 \quad 0] P_1^{(1)} [1 \quad 2 \quad 3 \quad 4 \quad 5]^T \right|$$

$$+ \left| e^{-0.9489+0.0440\times 2} + 0.61 - [1 \quad 0 \quad 0 \quad 0 \quad 0] P_1^{(2)} [1 \quad 2 \quad 3 \quad 4 \quad 5]^T \right|$$

$$+ \ldots$$

$$+ \left| e^{-0.9489+0.0440\times 6} + 0.61 - [1 \quad 0 \quad 0 \quad 0 \quad 0] P_1^{(6)} [1 \quad 2 \quad 3 \quad 4 \quad 5]^T \right| \qquad (5.5)$$

The transition probabilities for the second zone can be estimated by substituting $Q_0 P_1^{(6)}$ as the initial state vector Q_1.

$$Minimize \left| e^{-0.9489+0.0440\times 7} + 0.61 - [0.9088 \quad 0.0687 \quad 0.0222 \quad 0.0003 \quad 0] P_2^{(1)} [1 \quad 2 \quad 3 \quad 4 \quad 5]^T \right|$$

$$+ \left| e^{-0.9489+0.0440\times 8} + 0.61 - [0.9088 \quad 0.0687 \quad 0.0222 \quad 0.0003 \quad 0] P_2^{(2)} [1 \quad 2 \quad 3 \quad 4 \quad 5]^T \right|$$

$$+ \ldots$$

$$+ \left| e^{-0.9489+0.0440\times 12} + 0.61 - [0.9088 \quad 0.0687 \quad 0.0222 \quad 0.0003 \quad 0] P_2^{(6)} [1 \quad 2 \quad 3 \quad 4 \quad 5]^T \right| \qquad (5.6)$$

By optimizing the nonlinear equation for each zone, the transition probabilities, p_{ij}s, for 8-inch (200 mm) VC pipes are estimated and summarized in Table 5.5.

Table 5.6: Transition probabilities for 8-inch (200 mm) VC pipes

Age period	Transition Matrix	p_1	p_2	p_3	p_4	p_5
0 – 6	P_1	0.9842	0.8870	0.9894	0.9774	1
7 – 12	P_2	0.9849	0.9133	0.8687	0.8940	1
13 – 18	P_3	0.9832	0.9113	0.8778	0.8931	1
19 – 24	P_4	0.8743	0.9033	0.8986	0.9295	1
25 – 30	P_5	0.9624	0.8945	0.8997	0.9397	1
31 – 36	P_6	0.9453	0.8800	0.8884	0.9279	1
37 – 42	P_7	0.9157	0.8495	0.8608	0.9068	1
43 – 48	P_8	0.8578	0.7921	0.7977	0.8747	1
49 – 54	P_9	0.6455	0.5834	0.6150	0.7315	1
55 – 60	P_{10}	0	0	0	0	1

Based on these estimated transition probabilities, the Markov chain model predicts that the expected useful life for 8-inch (200 mm) VC pipes is 58 years. Since the analysis results are based only on the data for pipes installed since 1952, the expected useful life of the 8-inch (200 mm) VC pipes can be extended once more accurate data is accumulated for the analysis. The deterioration curve using the expected condition ratings from the Markov chain model is shown in Figure 5.2.

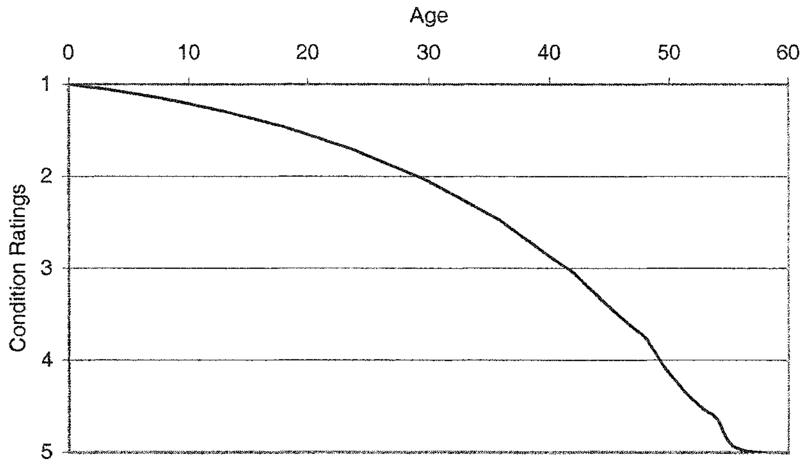


Figure 5.2: Deterioration curve for 8-inch (200 mm) VC pipes (nonlinear optimization-based approach)

As shown in Figure 5.2, the deterioration rate is low at the beginning of the useful life, and then increases as the sewer "ages." From this figure it can be inferred that if the condition rating 4 is set as the minimum acceptance level for the 8-inch (200 mm) VC pipes in the City of San Diego, the pipes deteriorate from the condition rating of 1 (best condition) to the condition of minimum acceptance level in approximately 5/6 of the expected useful life.

5.2.2 Ordered Probit Model-Based Approach

The nonlinear optimization-based approach can be used as a technique for the development of deterioration models for wastewater infrastructure assets as described in Section 5.2.1. However, in addition to the drawbacks described in Chapter 2, some other disadvantages exist when the nonlinear optimization-based approach is used.

First, as indicated by Madanat et al. (1995), the maximum number of transition probabilities that can be estimated using the nonlinear optimization given in equation (3.9) is equal to the total number of periods in each zone. Thus, since the periods used for a zone in this study were six years, a maximum of six transition probabilities can be estimated in a transition matrix resulting in the assumption that the condition levels of infrastructure assets do not drop more than one level in a transition. By making this assumption, only four transition probabilities are required to be estimated for a zone as shown in equation (5.3). However, it is possible for a condition state to move more than one level down during a transition period even though the possibility is not high. The nonlinear optimization-based approach does not provide information about these transitions.

Second, the regression function for 8-inch (200 mm) VC pipes given in equation (5.2) covers the range beyond the past data. The oldest pipe segment in the data set was 49 years old in 2001, whereas the regression function explains the relation between the condition ratings and ages up to 58 years. As indicated by Neter et al. (1996), if the regression function provides predictions far beyond the range of past data, special attention is needed in the interpretation of the results of the regression analysis.

Third, the application of the nonlinear optimization-based approach is restricted for a small number of data groups. As shown in the previous section, only one model out of 20 was valid as a deterioration model for the wastewater infrastructure assets in the City of San Diego. Consequently, the applicability of the ordered probit model associated with the incremental model for the development of deterioration models should be investigated and is presented in the next section.

5.2.2.1 Estimation of Parameters and Thresholds

For the estimation of transition probabilities for the Markov chain-based deterioration model, the ordered probit model was applied for condition states 1, 2, 3, and 4. Since the last condition state (condition state 5) is an absorbing state, only four ordered probit models are required. For this analysis, the entire data set, including different pipe sizes and materials, was used to investigate the effectiveness of the type of material and size on the deterioration rate.

Using the given data set, Statistical Software Tools (SST) (Dubin and Rivers 1987) was used to find the maximum likelihood estimator of the model parameters, β's, and thresholds, μ's, given in equation (3.15). A total of five variables were used in modeling process as shown in Table 5.7. However, depending on the availability of data, other variables such as depth of installation, source of sewer (industrial and residential), soils surrounding pipes, ground water level, traffic volume above pipe segments, and frequencies of overflow, can be included in the analysis. This information, however, was not available for this study.

Table 5.7: Variables used for ordered probit modeling

Name of Variable	Description of Variable
Length	Length of pipe segments between manholes in feet
Size	Diameter of pipe segments in inch
Type of material	Vitrified Clay or PVC
Age	Age at year 2001 from the installation year
Slope	Slope of pipe segments between manholes. Slope = (Elevation of upstream invert – Elevation of downstream invert) / Length

The results of estimates of the parameters and the thresholds for the ordered probit model for condition states 1, 2, 3, and 4 are presented in Tables 5.8, 5.9, 5.10, and 5.11 respectively. The estimation results show that the type of material is not a significant variable for the deterioration of wastewater infrastructure assets. However, if more data were available, the estimation may produce different results.

Table 5.8: Estimation results for ordered probit model (Condition state 1)

Name of Variable	Parameter Estimate	t-statistic
Constant	-2.387410	-5.013
Length	-0.000608	-1.309
Size	0.071457	1.600
Age	0.071174	14.043
Slope	1.717000	2.513
Threshold 1	0.986510	21.265
Threshold 2	1.606450	39.518
Threshold 3	2.157650	40.123

Number of observations = 545
$LL(0) = -1065.87$
$LL(\beta) = -767.24$
$\rho^2 = 0.280$

Table 5.9: Estimation results for ordered probit model (Condition state 2)

Name of Variable	Parameter Estimate	t-statistic
Constant	-1.641970	-2.864
Length	-0.002107	-3.739
Size	0.087300	1.810
Age	0.041571	5.571
Slope	2.562520	3.134
Threshold 1	0.696540	15.735
Threshold 2	1.28681	22.486

Number of observations = 442
$LL(0) = -698.45$
$LL(\beta) = -576.82$
$\rho^2 = 0.174$

Table 5.10: Estimation results for ordered probit model (Condition state 3)

Name of Variable	Parameter Estimate	t-statistic
Constant	-0.719260	-1.301
Length	-0.002062	-2.982
Age	0.031155	2.725
Slope	1.728870	1.876
Threshold 1	0.762620	10.564

Number of observations = 305
$LL(0) = -354.55$
$LL(\beta) = -323.35$
$\rho^2 = 0.088$

Table 5.11: Estimation results for ordered probit model (Condition state 4)

Name of Variable	Parameter Estimate	t-statistic
Length	-0.002109	-2.493
Size	0.051453	1.796
Slope	3.928490	2.590

Number of observations = 194

$LL(0) = -134.47$

$LL(\beta) = -124.52$

$\rho^2 = 0.074$

The estimation results show that in addition to the type of material, the size of pipe segments is not significant for the transitions of pipes in condition state 3 (Table 5.10). For condition state 4 (Table 5.11), age is not a significant variable for the transitions of pipes. This implies that the deterioration of the pipes in condition state 4 is not affected by age but rather by the length, size, and slope of the pipe segments, which cause the transition probability to remain stationary throughout the entire useful life.

The signs of the parameter estimates are consistent over the estimation results. Longer sewer runs are less likely to deteriorate at a faster rate than the shorter ones, which may be due to the fact that longer runs means less bends in the pipe to accumulate debris, creating blockages or damage to the pipe from standing sewage. Another possible reasoning is that the longer runs may be more of conveyance systems rather than collection systems, thus having fewer laterals connected to the pipes which can weaken a pipe system. For condition states 1, 2, and 4, larger pipes are more likely to have higher rates of deterioration, and this may be due to larger pipes having more surface area exposed to sewage and surrounding soils, possibly causing more damages. For condition states 1, 2, and 3, older pipes are more likely to deteriorate at a faster rate, which is consistent with the general perception of the deterioration rate of infrastructure assets, i.e., the deterioration rate is lower during the early years of useful life and higher during the later years. For all condition states, the steeper the slope is, the higher the possibility that pipe segments deteriorate. This may be due to the fact that steeper pipe segments induce faster flow rates, resulting in greater possibility for damage to the inside walls or joints of pipe segments.

The overall fit of the ordered probit model can be measured by the ρ^2statistic as shown in equation (5.7) (Washington et al. 2003).

$$\rho^2 = 1 - \frac{LL(\beta)}{LL(0)} \tag{5.7}$$

where, $LL(\beta)$ = log likelihood at convergence with parameter vector β

$LL(0)$ = initial log likelihood with all parameters set to zero

This ρ^2statistic is similar to R^2 in the regression models. Thus, the closer ρ^2statistic is to one, the better the estimated model is. As presented in Tables 5.8 through 5.11, the ρ^2statistics for condition states 1 and 2 are relatively acceptable. However, the ρ^2statistics for condition states 3 and 4 are smaller than expected to account for the effectiveness of the models.

5.2.2.2 Estimation of Transition Probabilities

The transition probabilities, i.e., the probabilities for the changes in condition rating (increments), for each condition state can be estimated using the obtained β's and μ's incorporated with standard normal distribution as shown in equation (3.18). The procedures for the estimation of transition probabilities based on the average individual procedure are shown in Figure 5.3.

For each 8-inch (200 mm) VC pipe segment, the values for the variables, except age, in the ordered probit model were applied to estimate the transition probabilities for each condition state. By increasing the age from one to the years appropriate for expected useful life, the transition probabilities for each condition state over the years can be estimated. After repeating this process for all pipe segments, the average transition probabilities for condition state 1 can be estimated. Repeating the procedures produces estimates of the transition probabilities for condition states 1, 2, 3, and 4. By adding the last row for the absorbing state, transition matrices for each year can be composed.

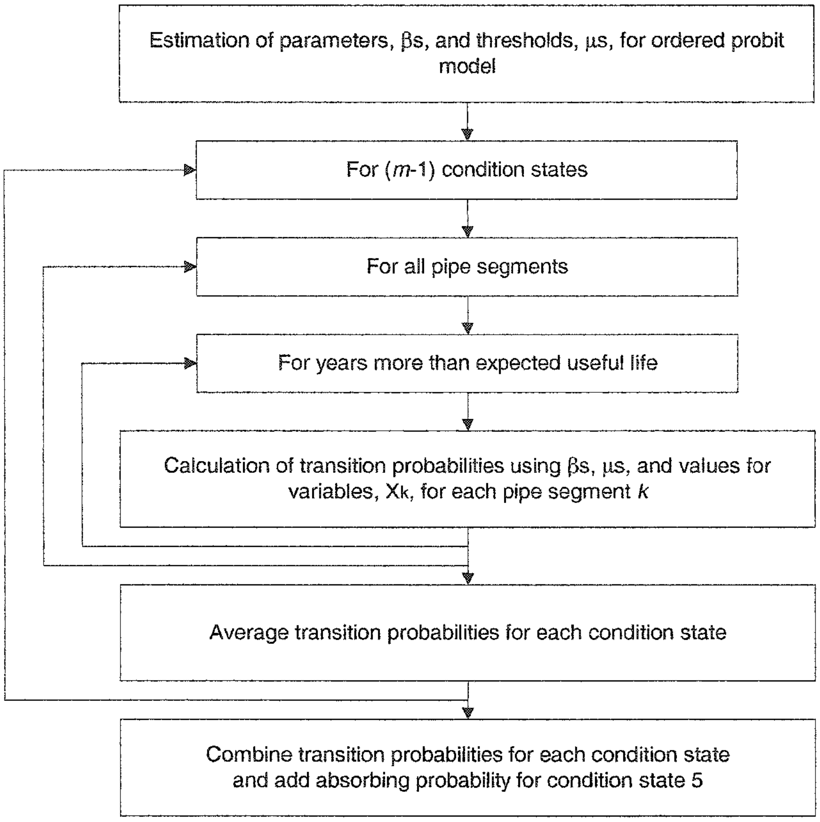


Figure 5.3: Procedures for the estimation of transition probabilities based on average individual procedure

Unlike the transition matrices obtained using the nonlinear optimization-based approach, these transition matrices will differ from year to year. Some of the transition probabilities based on ordered probit model are presented in Table 5.12, and the entire estimated transition probabilities for 8-inch (200 mm) VC pipes over 70 years are shown in Appendix B.

Table 5.12: Estimated transition probabilities based on ordered probit model

Age	P_{11}	P_{12}	P_{13}	P_{14}	P_{15}	P_{22}	P_{23}	P_{24}	P_{25}	P_{33}	P_{34}	P_{35}	P_{44}	P_{45}
1	0.961	0.036	0.003	0.000	0.000	0.862	0.096	0.030	0.013	0.842	0.117	0.041	0.446	0.554
2	0.955	0.041	0.003	0.000	0.000	0.853	0.101	0.032	0.014	0.834	0.121	0.044	0.446	0.554
3	0.948	0.047	0.004	0.001	0.000	0.844	0.106	0.035	0.015	0.827	0.126	0.047	0.446	0.554
4	0.940	0.054	0.005	0.001	0.000	0.835	0.111	0.037	0.017	0.819	0.131	0.050	0.446	0.554
5	0.931	0.062	0.006	0.001	0.000	0.825	0.117	0.040	0.018	0.811	0.136	0.053	0.446	0.554
6	0.921	0.070	0.007	0.001	0.000	0.815	0.123	0.043	0.020	0.803	0.141	0.056	0.446	0.554
7	0.911	0.079	0.009	0.001	0.000	0.804	0.128	0.046	0.022	0.794	0.146	0.060	0.446	0.554
8	0.899	0.089	0.010	0.002	0.000	0.793	0.134	0.049	0.024	0.786	0.151	0.064	0.446	0.554
9	0.886	0.099	0.012	0.002	0.000	0.782	0.140	0.052	0.026	0.777	0.156	0.067	0.446	0.554
10	0.872	0.111	0.014	0.003	0.001	0.771	0.146	0.055	0.028	0.768	0.161	0.071	0.446	0.554

Using the transition probabilities estimated based on the ordered probit model and equation (3.10), the expected condition ratings were computed. These computation results were used for drawing the deterioration curve presented in Figure 5.4.

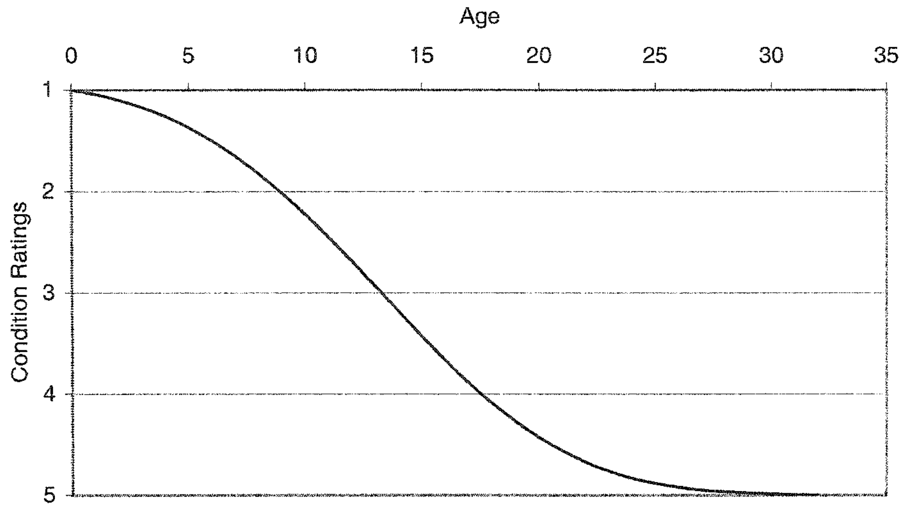


Figure 5.4: Deterioration curve for 8-inch (200 mm) VC pipes (econometric model-based approach)

As shown in Figure 5.4, the deterioration rate is low during the early years, increases during the mid-years, and becomes low again during the later years. However, the overall deterioration rate obtained based on the ordered probit model is greater than the one obtained from the nonlinear optimization-based approach. For this reason, the estimated time periods for 8-inch (200 mm) VC pipes to move from condition state 1 to 2, 2 to 3, 3 to 4, and 4 to 5 are approximately 9, 5, 4, and 14 years, respectively, resulting in an expected useful life of 32 years.

5.2.2.3 Deterioration Model for Asset Valuation

The ordered probit model-based approach provides advantages over the nonlinear optimization-based approach in the development of deterioration models for wastewater infrastructure assets. The ordered probit model explicitly identifies the deterioration process in terms of exogenous variables, which enables estimation of the transition probabilities for a specific pipe segment or for a specific group of pipes. It also allows determination of the annual transition probabilities. Using this method, more than two transition probabilities can be estimated per row in a transition matrix. These advantages make the analysis independent of the assumptions needed for the nonlinear optimization-based approach such as grouping the entire data set into subgroups based on the type of material and pipe sizes, zoning the analysis period and assuming transition probabilities being stationary in a zone, and assuming that condition states do not drop more than one condition level during a transition period. The ordered probit model-based approach recognizes the ordinal and discrete nature of the condition rating data, whereas the nonlinear optimization-based approach does not consider the ordinal scale of the condition rating data and uses the continuous values obtained from regression analysis.

However, the results from the analysis using the ordered probit model are not sufficiently accurate to use as the deterioration model of wastewater infrastructure assets in the City of San Diego. As shown in the previous section, the expected useful life estimated using the ordered probit model is 32 years, which is far less than the actual ages of the existing pipes. The estimated time periods for transitions between condition states are too short to be reasonable, and measurement of goodness-of-fit for the ordered probit model, ρ^2 statistic, is low for condition states 3 and 4, making the application of the analysis results questionable. These drawbacks may be due to the lack of integrity in the data set. In the case of Madanat et al. (1995), panel data were used in the analysis, while only cross-sectional data were available for the analysis in this study. Another reason for producing the poor results may be the measurement errors included in the data set.

Even though the ordered probit model-based approach is theoretically and statistically sound, the outputs of deterioration modeling are not satisfactory for analyzing the value of wastewater infrastructure assets in the City of San Diego because of the short expected useful life and low ρ^2 statistics. On the other hand, in spite of the drawbacks, the nonlinear optimization-based approach provides acceptable deterioration models and is still employed in the development of deterioration models for infrastructure assets such as pavement and bridge systems. When sufficient data are available, such as panel data, and further research is performed to reduce the measurement errors in condition assessment, the econometric model based-approach, including the ordered probit model, may be a good method for the development of deterioration models for wastewater infrastructure assets. However, until then, the nonlinear optimization-based approach can be applied for the development of deterioration models for wastewater infrastructure assets. In this study, the deterioration model obtained from the nonlinear optimization-based approach is employed and used for the valuation of wastewater infrastructure assets.

5.3 Valuation of Wastewater Infrastructure Assets

The values of wastewater infrastructure assets are estimated using the depreciation method (book value), the modified approach, and the deterioration–based valuation method (deteriorated value) as described in Chapter 4. Life cycle cost analysis (LCCA) based on dynamic programming optimization technique using the value iteration method is performed to identify the optimal maintenance and repair (M & R) alternatives for the pipe segments. Based on the recommended M & R alternatives, the values of wastewater infrastructure assets are estimated for different investment plans in this section.

5.3.1 Life Cycle Cost Analysis for M & R Alternatives

The optimal M & R alternatives for wastewater infrastructure assets that minimize the costs can be selected using the dynamic programming optimization technique as shown in equation (4.13). A total of seven M & R activities were considered as the candidates for the optimal alternatives as presented in Table 4.1. The applicability of the considered M & R alternatives is summarized in Table 4.2.

The transition probability for the routine cleaning or no action activities can be obtained from the deterioration model. The transition matrix for the first zone (from year 1 to year 6) when routine cleaning is performed is given in equation (5.8).

$$P=\begin{bmatrix}0.9842 & 0.0158 & 0 & 0 & 0\\ 0 & 0.8870 & 0.1130 & 0 & 0\\ 0 & 0 & 0.9894 & 0.0106 & 0\\ 0 & 0 & 0 & 0.9774 & 0.0226\\ 0 & 0 & 0 & 0 & 1\end{bmatrix} \tag{5.8}$$

The transition matrix for the grouting alternative can be composed using the concept presented in equation (4.3) and given in equation (5.9).

$$P=\begin{bmatrix}0.9842 & 0.0158 & 0 & 0 & 0\\ 0.9842 & 0.0158 & 0 & 0 & 0\\ 0 & 0.8870 & 0.1130 & 0 & 0\\ 0 & 0 & 0.9894 & 0.0106 & 0\\ 0 & 0 & 0 & 0.9774 & 0.0226\end{bmatrix} \tag{5.9}$$

Assuming that the condition states return to the initial condition after rehabilitation or replacement activities are applied to the existing pipe segments, the transition matrix for cured-in-place pipe (CIPP) lining, sliplining, pipe bursting, and open-cut replacement can be expressed as shown in equation (5.10).

$$P=\begin{bmatrix}1.0 & 0 & 0 & 0 & 0\\ 1.0 & 0 & 0 & 0 & 0\\ 1.0 & 0 & 0 & 0 & 0\\ 1.0 & 0 & 0 & 0 & 0\\ 1.0 & 0 & 0 & 0 & 0\end{bmatrix} \tag{5.10}$$

The costs for M & R alternatives for 8-inch (200 mm) VC pipes are tabulated in Table 5.13. The costs for M & R activities, except pipe bursting, are obtained from the estimations for M & R costs for the City of Indianapolis in 1998 (ACE 1988). These costs are adjusted for inflation using the Construction Cost Index (CCI) provided by

Engineering News Record (ENR) for year 2001 (CCI = 6,343) and year 1998 (CCI = 5,920) (ENR CCI 2003). These costs are adjusted again for location using RS Means location factors for heavy construction for the City of Indianapolis (95.9) and the City of San Diego (105.8) (RS Means 2002).

Table 5.13: Costs for M & R alternatives

Condition State (i)	M & R Alternatives (a) and costs ($/LF)						
	NA	RC	GR	CIPP	SL	PB	OR
1	0	6	12	59	30	58	83
2	0	6	12	59	30	58	83
3			12	59	30	58	83
4				59	30	58	83
5						58	83

Using this information and the procedure for the value iteration method described in Chapter 4, optimal M & R alternatives were selected for different analysis periods. The discount rate of one was used in this study. The results of optimization using the dynamic programming are presented Tables 5.14, 5.15, and 5.16, for analysis periods of 1, 11, and 31 years respectively. The optimal M & R alternatives change from these analysis periods, and the unit for the costs in these tables is dollar per linear foot. The optimal M & R alternatives for the different analysis periods are summarized in Table 5.17 and the results of the optimization process for 40 years are presented in Appendix C.

Table 5.14: Results of optimization using dynamic programming (analysis period 1)

Condition State (i)	$f_n(i) = \min_{a} \{C_n(i,a) + \alpha \sum_{j=1}^{5} p(j \mid i,a,n) f_{n-1}(i)\}$ ($/LF)							$f_1(i)$ ($/LF)	a
	NA	RC	GR	CIPP	SL	PB	OR		
1	0	6	12	59	30	58	83	0	NA
2	1	7	12	59	30	58	83	1	NA
3			13	59	30	58	83	13	GR
4				59	30	58	83	30	SL
5						58	83	58	PB

Table 5.15: Results of optimization using dynamic programming (analysis period 11)

Condition State (i)	$f_n(i) = \min_{a} \{C_n(i,a) + \alpha \sum_{j=1}^{5} p(j \mid i,a,n) f_{n-1}(i)\}$ ($/LF)							$f_{11}(i)$ ($/LF)	a
	NA	RC	GR	CIPP	SL	PB	OR		
1	1	7	13	60	30	59	84	1	NA
2	13.1	19	12.8	60	30	59	84	13	GR
3			25	60	30	59	84	25	GR
4				60	30	59	84	30	SL
5						59	84	59	PB

Table 5.16: Results of optimization using dynamic programming (analysis period 31)

Condition State (i)	$f_n(i) = \min_{a} \{C_n(i,a) + \alpha \sum_{j=1}^{5} p(j \mid i,a,n) f_{n-1}(i)\}$ ($/LF)							$f_{31}(i)$ ($/LF)	a
	NA	RC	GR	CIPP	SL	PB	OR		
1	89	13	19	66	36	65	89	13	RC
2	89	26	19	66	36	65	89	19	GR
3			32	66	36	65	89	32	GR
4				66	36	65	89	36	SL
5						65	89	65	PB

Table 5.17: Optimal M & R alternatives

Condition State (i)	Analysis Period		
	1 – 10 years	11 – 30 years	≥ 31 years
1	No action	No action	Routine cleaning
2	No action	Grouting	Grouting
3	Grouting	Grouting	Grouting
4	Sliplining	Sliplining	Sliplining
5	Pipe bursting	Pipe bursting	Pipe bursting

As shown in Table 5.17, for the analysis period of one to 10 years, the optimal M & R alternatives for condition states 1, 2, 3, 4, and 5 are no action, no action, grouting, sliplining, and pipe bursting respectively. For the analysis period of 11 years to 30 years, the optimal treatments for the pipe segments in condition states 1, 2, 3, 4, and 5 are no action, grouting, grouting, sliplining, and pipe bursting respectively. When the analysis period is greater than 30 years, routine cleaning, grouting, grouting, sliplining, and pipe bursting are recommended for the pipes in condition states 1, 2, 3, 4, and 5 respectively. One point that should be noted in the results of the optimization process is that cost is the only consideration for the selection of M & R alternatives. For pipe bursting, other factors such as constructibility and effectiveness of the treatment may be included in the decision-making process.

5.3.2 Impacts of Life Cycle Cost Analysis on Asset Values

In this section the values of wastewater infrastructure assets are estimated using the depreciation method (book value), the modified approach, and the deterioration-based valuation method (deteriorated value). The impacts of the M & R treatments obtained from LCCA on asset values are investigated based on different future investment scenarios.

5.3.2.1 Pipe Segments for Analysis

For the estimation process of the values of wastewater infrastructure assets, 25 pipe segments were randomly extracted from the data set of 8-inch (200 mm) VC pipes. As shown in Table 5.18, each condition state includes five pipe segments, which have a total length of 4,250 ft (1,295 m) and installation years ranging from 1962 to 1987.

Table 5.18: Pipe segments for analysis

No.	FSN	Length (ft)	Size (inch)	Material	Year	Rating
1	51115	54	8	VC	1965	5
2	39249	78	8	VC	1962	5
3	57459	123	8	VC	1962	5
4	57966	143	8	VC	1962	5
5	14520	333	8	VC	1968	5
6	14783	16	8	VC	1968	4
7	58572	67	8	VC	1966	4
8	51488	117	8	VC	1966	4
9	51938	193	8	VC	1966	4
10	51507	298	8	VC	1966	4
11	59279	37	8	VC	1987	3
12	51474	118	8	VC	1965	3
13	51444	174	8	VC	1968	3
14	19105	246	8	VC	1975	3
15	58571	342	8	VC	1966	3
16	18434	127	8	VC	1971	2
17	852	202	8	VC	1980	2
18	58769	268	8	VC	1973	2
19	58798	295	8	VC	1973	2
20	19261	351	8	VC	1979	2
21	212	188	8	VC	1985	1
22	44827	215	8	VC	1982	1
23	51386	30	8	VC	1984	1
24	51462	170	8	VC	1980	1
25	5041025	65	8	VC	1987	1
	Total	4,250				

FSN = Facility Sequential Number

5.3.2.2 Case 1: Values of Wastewater Infrastructure Assets in Base Year

For the estimation process of asset values, open-cut replacement cost was used as the base value. The unit cost for open-cut replacement given in Table 5.13 was adjusted for inflation between the installation year and year 2001 using ENR CCI and then multiplied by the length of the pipe segments to provide the replacement costs in constant dollars.

The asset values of the pipe segments in 2001 that were estimated using different valuation methods are presented in Table 5.19. These values were estimated based on the assumption that no M & R activities were applied to the pipes since their installation.

In Table 5.19 the current deteriorated values of the selected pipe segments were estimated using equation (3.19). The deteriorated values show that the pipe segments in condition state 5 have $0 values while the pipes in condition state 1 have the same value as the base value. The book value represents the asset values based on the straight-line depreciation method, whereby salvage value of $0 was assumed and a useful life of 58 years was used. Therefore, older pipes have less value than the newer pipes when this depreciation method is used. The asset values estimated using the modified approach are the same as the base values since no improvement activities were performed. The total asset values for the pipe segments estimated using the three different valuation methods are presented in Figure 5.5.

Table 5.19: Estimated asset values in 2001 (base year)

(1) No.	(2) FSN	(3) Length (ft)	(4) Size (inch)	(5) Material	(6) Year	(7) M & R Alternative	(8) Unit Cost ($/LF)	(9) M & R Cost	(10) Base Value	(11) Rating	(12) Deteriorated Value	(13) Book Value	(14) Modified Approach
1	51115	54	8	VC	1965	Pipe Bursting	$58	$3,142	$684	5	$0	$259	$684
2	39249	78	8	VC	1962	Pipe Bursting	$58	$4,539	$887	5	$0	$291	$887
3	57459	123	8	VC	1962	Pipe Bursting	$58	$7,157	$1,399	5	$0	$458	$1,399
4	57966	143	8	VC	1962	Pipe Bursting	$58	$8,321	$1,627	5	$0	$533	$1,627
5	14520	333	8	VC	1968	Pipe Bursting	$58	$19,377	$5,017	5	$0	$2,163	$5,017
6	14783	16	8	VC	1968	Sliplining	$30	$473	$241	4	$60	$104	$241
7	58572	67	8	VC	1966	Sliplining	$30	$1,980	$891	4	$223	$353	$891
8	51488	117	8	VC	1966	Sliplining	$30	$3,457	$1,555	4	$389	$617	$1,555
9	51938	193	8	VC	1966	Sliplining	$30	$5,703	$2,566	4	$641	$1,017	$2,566
10	51507	298	8	VC	1966	Sliplining	$30	$8,805	$3,961	4	$990	$1,571	$3,961
11	59279	37	8	VC	1987	Grouting	$12	$437	$2,127	3	$1,063	$1,613	$2,127
12	51474	118	8	VC	1965	Grouting	$12	$1,395	$1,495	3	$747	$567	$1,495
13	51444	174	8	VC	1968	Grouting	$12	$2,056	$2,622	3	$1,311	$1,130	$2,622
14	19105	246	8	VC	1975	Grouting	$12	$2,907	$7,098	3	$3,549	$3,916	$7,098
15	58571	342	8	VC	1966	Grouting	$12	$4,042	$4,546	3	$2,273	$1,803	$4,546
16	18434	127	8	VC	1971	No Action	$0	$0	$2,619	2	$1,964	$1,264	$2,619
17	852	202	8	VC	1980	No Action	$0	$0	$8,530	2	$6,397	$5,441	$8,530
18	58769	268	8	VC	1973	No Action	$0	$0	$6,625	2	$4,969	$3,427	$6,625
19	58798	295	8	VC	1973	No Action	$0	$0	$7,292	2	$5,469	$3,772	$7,292
20	19261	351	8	VC	1979	No Action	$0	$0	$13,750	2	$10,313	$8,535	$13,750
21	212	188	8	VC	1985	No Action	$0	$0	$10,288	1	$10,288	$7,450	$10,288
22	44827	215	8	VC	1982	No Action	$0	$0	$10,728	1	$10,728	$7,214	$10,728
23	51386	30	8	VC	1984	No Action	$0	$0	$1,623	1	$1,623	$1,147	$1,623
24	51462	170	8	VC	1980	No Action	$0	$0	$7,179	1	$7,179	$4,579	$7,179
25	5041025	65	8	VC	1987	No Action	$0	$0	$3,736	1	$3,736	$2,834	$3,736
	Total	4,250						$73,792	$109,085	3	$73,913	$62,059	$109,085

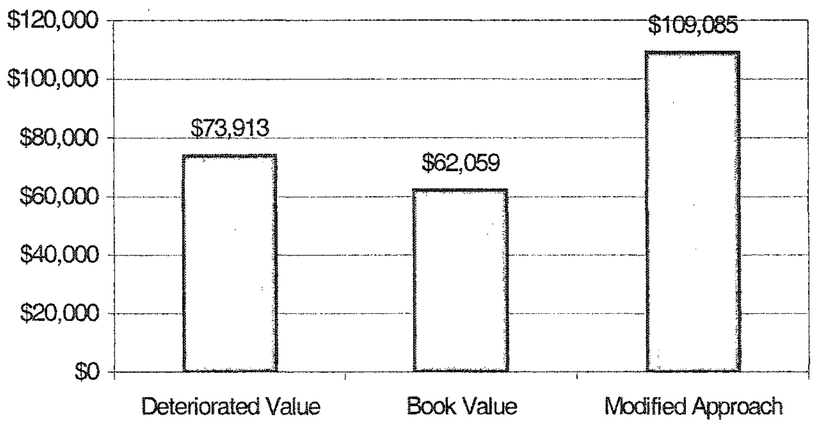


Figure 5.5: Estimated asset values in year 2001 (base year)

The values of the pipes based on the deteriorated value method, the depreciation method, and the modified approach are $73,913, $62,059, and $109,085 respectively, which demonstrates the significant variations in asset values depending on the valuation method used. For instance, the book value is 26% less than the deteriorated value while the modified approach-based value is 48% greater than the deteriorated value. A larger gap can be observed between the values estimated using the depreciation method and the modified approach. When the modified approach is used to estimate the value of the considered pipe segments, the asset value is 76% greater than that estimated by the depreciation method. Therefore, considering the substantial variations in asset values, special attention should be paid to the selection of a valuation method and interpretation of values of wastewater infrastructure assets.

The asset values of the pipe segments in each condition state are calculated to investigate the variations in asset values and are summarized in Table 5.20.

Table 5.20: Asset values for the pipes in each condition state (base year)

Condition State	Deteriorated Value	Book Value		Modified Approach	
		Value	%	Value	%
1	$33,553	$23,224	69 %	$33,553	100 %
2	$29,112	$22,439	77 %	$38,817	133 %
3	$8,944	$9,029	101 %	$17,888	200%
4	$2,303	$3,662	159 %	$9,214	400%
5	$0	$3,704	∞	$9,614	∞

As shown in Table 5.20, the estimated book values are less than the deteriorated values for the pipes in condition states 1 and 2 while they are greater than the deteriorated values for condition states 4 and 5. The pipes in condition states 1, 2, 3, 4, and 5 were installed in the 1980s, 1970s, 1960s and 1970s, late 1960s, and early 1960s respectively (Table 5.18), which implies that when the depreciation method is used, the loss in asset values due to depreciation is greater than the loss from deterioration for relatively new pipe segments and it is smaller for older pipes. Therefore, the asset values estimated using the depreciation method for condition states 1 and 2 are 31% and 23% less than the values from the deteriorated value method. The value obtained from the depreciation method for condition state 4 is 59% greater than the value obtained from the deteriorated value method.

On the other hand, when the modified approach is used, the estimated values are always greater than the values obtained using the deteriorated value method, which occurs because the modified approach does not consider the deterioration of wastewater infrastructure assets in the valuation process. As shown in Table 5.20, the value from the modified approach for condition state 4 is four times greater than the value obtained using the deteriorated value method.

For condition state 5, significant differences can be observed among the values obtained from the three valuation methods. The difference between the deteriorated value and the book value is equal to the values obtained by subtracting depreciation from the base value. The difference between the deteriorated value and the modified approach-based value is equal to the base value. Therefore, the values of wastewater infrastructure assets for the municipalities where the infrastructure assets are in the worst condition states may show crucial variations depending on the method employed for the asset valuation process.

5.3.2.3 Case 2: The Assets Are Repaired Over One Year

To investigate the changes in asset values based on future investment plans, different scenarios are assumed and applied for the valuation using the three valuation methods. In this section, it is assumed that the entire pipe segments in condition states 3, 4, and 5 were repaired using the M & R alternatives recommended by LCCA during the year after the base year. The required budget for M & R is \$73,792. The estimated asset values for this case are tabulated in Table 5.21.

In Table 5.21, the deteriorated value can be computed using equation (3.24), in which the expected total added value (ETAV) is incorporated. The ETAV for grouting, sliplining, and pipe bursting can be computed using the equations (5.8), (5.9) and (5.10) respectively.

$$
\begin{aligned}
v_i &= \sum_j p_{ij} c_{ij} \\
&= \begin{bmatrix} 0.9842 & 0.0158 & 0 & 0 & 0 \\ 0.9842 & 0.0158 & 0 & 0 & 0 \\ 0 & 0.8870 & 0.1130 & 0 & 0 \\ 0 & 0 & 0.9894 & 0.0106 & 0 \\ 0 & 0 & 0 & 0.9774 & 0.0226 \end{bmatrix} \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & c_{32} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad \text{(grouting)} \qquad (5.8) \\
&= 0.8870 c_{32}
\end{aligned}
$$

where, c_{32} = cost for grouting

Table 5.21: Estimated asset values in year 1 (1-year investment plan)

(1) No.	(2) FSN	(3) Length (ft)	(4) Size (inch)	(5) Material	(6) Year	(7) M & R Alternative	(8) Unit Cost ($/LF)	(9) M & R Cost	(10) Base Value	(11) Rating	(12) Deteriorated Value	(13) Expected Added Value	(14) Deteriorated Value = (12)+(13)	(15) Book Value	(16) Modified Approach
1	51115	54	8	VC	1965	Pipe Bursting	$58	$3,142	$684	5	$0	$3,142	$3,142	$3,390	$3,826
2	39249	78	8	VC	1962	Pipe Bursting	$58	$4,539	$887	5	$0	$4,539	$4,539	$4,814	$5,426
3	57459	123	8	VC	1962	Pipe Bursting	$58	$7,157	$1,399	5	$0	$7,157	$7,157	$7,592	$8,557
4	57966	143	8	VC	1962	Pipe Bursting	$58	$8,321	$1,627	5	$0	$8,321	$8,321	$8,826	$9,948
5	14520	333	8	VC	1968	Pipe Bursting	$58	$19,377	$5,017	5	$0	$19,377	$19,377	$21,453	$24,395
6	14783	16	8	VC	1968	Sliplining	$30	$473	$241	4.14	$52	$473	$524	$573	$714
7	58572	67	8	VC	1966	Sliplining	$30	$1,980	$891	4.14	$191	$1,980	$2,171	$2,317	$2,870
8	51488	117	8	VC	1966	Sliplining	$30	$3,457	$1,555	4.14	$333	$3,457	$3,790	$4,047	$5,012
9	51938	193	8	VC	1966	Sliplining	$30	$5,703	$2,566	4.14	$550	$5,703	$6,253	$6,676	$8,268
10	51507	298	8	VC	1966	Sliplining	$30	$8,805	$3,961	4.14	$849	$8,805	$9,654	$10,308	$12,766
11	59279	37	8	VC	1987	Grouting	$12	$437	$2,127	3.05	$1,034	$388	$1,422	$2,014	$2,127
12	51474	118	8	VC	1965	Grouting	$12	$1,395	$1,495	3.05	$727	$1,237	$1,964	$1,936	$1,495
13	51444	174	8	VC	1968	Grouting	$12	$2,056	$2,622	3.05	$1,275	$1,824	$3,099	$3,141	$2,622
14	19105	246	8	VC	1975	Grouting	$12	$2,907	$7,098	3.05	$3,452	$2,579	$6,031	$6,701	$7,098
15	58571	342	8	VC	1966	Grouting	$12	$4,042	$4,546	3.05	$2,211	$3,585	$5,796	$5,766	$4,546
16	18434	127	8	VC	1971	No Action	$0	$0	$2,619	2.06	$1,928	$0	$1,928	$1,219	$2,619
17	852	202	8	VC	1980	No Action	$0	$0	$8,530	2.06	$6,279	$0	$6,279	$5,294	$8,530
18	58769	268	8	VC	1973	No Action	$0	$0	$6,625	2.06	$4,877	$0	$4,877	$3,313	$6,625
19	58798	295	8	VC	1973	No Action	$0	$0	$7,292	2.06	$5,368	$0	$5,368	$3,646	$7,292
20	19261	351	8	VC	1979	No Action	$0	$0	$13,750	2.06	$10,122	$0	$10,122	$8,297	$13,750
21	212	188	8	VC	1985	No Action	$0	$0	$10,288	1.02	$10,247	$0	$10,247	$7,273	$10,288
22	44827	215	8	VC	1982	No Action	$0	$0	$10,728	1.02	$10,685	$0	$10,685	$7,029	$10,728
23	51386	30	8	VC	1984	No Action	$0	$0	$1,623	1.02	$1,616	$0	$1,616	$1,119	$1,623
24	51462	170	8	VC	1980	No Action	$0	$0	$7,179	1.02	$7,150	$0	$7,150	$4,456	$7,179
25	5041025	65	8	VC	1987	No Action	$0	$0	$3,736	1.02	$3,721	$0	$3,721	$2,770	$3,736
	Total	4,250						$73,792	$109,085	3.05	$72,668	$72,567	$145,235	$133,969	$172,039

$$v_i = \sum_j p_{ij} c_{ij}$$

$$= \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ c_{41} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \text{(sliplining)} \qquad (5.9)$$

$$= c_{41}$$

where, c_{41} = cost for sliplining

$$v_i = \sum_j p_{ij} c_{ij}$$

$$= \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ c_{51} & 0 & 0 & 0 & 0 \end{bmatrix} \text{(pipe bursting)} \qquad (5.10)$$

$$= c_{51}$$

where, c_{51} = cost for pipe bursting

As shown in Table 5.21, the condition ratings are slightly downgraded since the base year. Based on the new condition ratings given in column (11), the deteriorated values in column (12) can be computed. By adding the ETAVs for each M & R activity to the deteriorated values, the updated deteriorated values in column (14) can be calculated.

The book values in Table 5.21 can be computed by subtracting the annual depreciation from the previous year's book value, and then adding the M & R costs for grouting, sliplining, and pipe bursting, depending upon the applicability. The modified approach produces asset values by adding the costs for sliplining and pipe bursting to the base value of the related pipe segment. Thus, the pipe segments receiving pipe bursting and sliplining treatments experience the increases in asset value while other pipes do not.

The resulting asset values estimated using the deteriorated value method, the depreciation method, and the modified approach are $145,235, $133,969, and $172,039 respectively.

The loss of value due to deterioration and depreciation and the gain of value from M & R investments are presented in Table 5.22. When using the deteriorated value method, a loss of $1,244 is experienced due to deterioration from the base year, and a gain of $72,567 is generated from the investments in M & R activities. The book value also undergoes a loss of $1,881 due to depreciation and a gain of $73,792 from M & R investments. When the modified approach is used, there is no loss in asset value. A total of $62,954 is gained during one year from the investments for sliplining and pipe bursting. As a result, there are increases in asset value by $71,323, $71,911, and $62,954 when the deteriorated value method, the depreciation method, and the modified approach are used respectively.

Table 5.22: Loss and gains in asset values for year 1 (1-year investment plan)

	Deteriorated Value	Book Value	Modified Approach
Loss	$1,244	$1,881	$0
Gain	$72,567	$73,792	$62,954
Total	$71,323	$71,911	$62,954

5.3.2.4 Case 3: The Assets Are Repaired Over Three Years

In this case, the funds are assumed to be available for repairing the pipe segments in condition states 5, 4, and 3 during year 1, 2, and 3 respectively. Therefore, the required budgets for M & R of the considered wastewater infrastructure assets are $42,537, $20,417, and $10,838 for the next three years. The asset values estimated using the three valuation methods according to the investment plan for three years are presented in Tables 5.23, 5.24, and 5.25.

The deteriorated values were computed using the logic shown in Figures 4.7 and 4.8 and related equations from (4.17) through (4.21), depending upon the history of treatment and the current condition state. For instance, the pipe segments in condition state 5 are replaced using pipe bursting during year 1. Other pipe segments receive no M

& R treatments and tend to deteriorate further (Table 5.23). The investments for pipe bursting are added to estimate the deteriorated value in year 1. During year 2, the pipe segments replaced by pipe bursting during year 1 deteriorated to condition rating 1.02, resulting in a loss of value from the previous year's deteriorated value (shown in column (14) in Table 5.23). Since these pipes are in condition state 1, no action is the optimal alternative for these pipes as shown in column (7) in Table 5.24. During year 2, the pipe segments in condition state 4 are rehabilitated using sliplining. During this period, the pipe segments in condition states 3, 2, and 1 continue to deteriorate, while the pipe segments originally in condition state 5 deteriorate from condition state 1 after the pipe bursting treatment is applied as shown in column (11) in Table 5.24. In Table 5.25, the pipe segments in condition state 3 are repaired using the grouting treatment during year 3; and other pipe segments require no treatments since they were repaired during previous years. However, as the pipes deteriorate, a minor loss is observed in the asset values of the pipes other than those in condition state 3.

The book value can be estimated by subtracting the annual depreciation from the previous year's book value, and then adding the investments for pipe bursting, sliplining, and grouting. The estimated values based on the modified approach were obtained by adding the investments for pipe bursting and sliplining to the previous year's asset values. Therefore, the deteriorated value and book value experience losses in asset value due to deterioration and depreciation while the modified approach-based value does not consider any loss in its valuation process. The difference between the deteriorated value method and the depreciation method is that the loss in asset value based the deteriorated value of a pipe segment becomes larger as time goes by, while the loss from the depreciation method is constant throughout the useful life of the pipe segment.

Table 5.23: Estimated asset values in year 1 (3-year investment plan)

(1) No.	(2) FSN	(3) Length (ft)	(4) Size (inch)	(5) Material	(6) Year	(7) M & R Alternative	(8) Unit Cost ($/LF)	(9) M & R Cost	(10) Base Value	(11) Rating	(12) Deteriorated Value	(13) Expected Added Value	(14) Deteriorated Value =(12)+(13)	(15) Book Value	(16) Modified Approach
1	51115	54	8	VC	1965	Pipe Bursting	$58	$3,142	$684	5	$0	$3,142	$3,142	$3,390	$3,826
2	39249	78	8	VC	1962	Pipe Bursting	$58	$4,539	$887	5	$0	$4,539	$4,539	$4,814	$5,426
3	57459	123	8	VC	1962	Pipe Bursting	$58	$7,157	$1,399	5	$0	$7,157	$7,157	$7,592	$8,557
4	57966	143	8	VC	1962	Pipe Bursting	$58	$8,321	$1,627	5	$0	$8,321	$8,321	$8,826	$9,948
5	14520	333	8	VC	1968	Pipe Bursting	$58	$19,377	$5,017	5	$0	$19,377	$19,377	$21,453	$24,395
6	14783	16	8	VC	1968	Sliplining	$30	$0	$241	4.14	$52	$0	$52	$100	$241
7	58572	67	8	VC	1966	Sliplining	$30	$0	$891	4.14	$191	$0	$191	$338	$891
8	51488	117	8	VC	1966	Sliplining	$30	$0	$1,555	4.14	$333	$0	$333	$590	$1,555
9	51938	193	8	VC	1966	Sliplining	$30	$0	$2,566	4.14	$550	$0	$550	$973	$2,566
10	51507	298	8	VC	1966	Sliplining	$30	$0	$3,961	4.14	$849	$0	$849	$1,503	$3,961
11	59279	37	8	VC	1987	Grouting	$12	$0	$2,127	3.05	$1,034	$0	$1,034	$1,577	$2,127
12	51474	118	8	VC	1965	Grouting	$12	$0	$1,495	3.05	$727	$0	$727	$541	$1,495
13	51444	174	8	VC	1968	Grouting	$12	$0	$2,622	3.05	$1,275	$0	$1,275	$1,085	$2,622
14	19105	246	8	VC	1975	Grouting	$12	$0	$7,098	3.05	$3,452	$0	$3,452	$3,794	$7,098
15	58571	342	8	VC	1966	Grouting	$12	$0	$4,546	3.05	$2,211	$0	$2,211	$1,724	$4,546
16	18434	127	8	VC	1971	No Action	$0	$0	$2,619	2.06	$1,928	$0	$1,928	$1,219	$2,619
17	852	202	8	VC	1980	No Action	$0	$0	$8,530	2.06	$6,279	$0	$6,279	$5,294	$8,530
18	58769	268	8	VC	1973	No Action	$0	$0	$6,625	2.06	$4,877	$0	$4,877	$3,313	$6,625
19	58798	295	8	VC	1973	No Action	$0	$0	$7,292	2.06	$5,368	$0	$5,368	$3,646	$7,292
20	19261	351	8	VC	1979	No Action	$0	$0	$13,750	2.06	$10,122	$0	$10,122	$8,297	$13,750
21	212	188	8	VC	1985	No Action	$0	$0	$10,288	1.02	$10,247	$0	$10,247	$7,273	$10,288
22	44827	215	8	VC	1982	No Action	$0	$0	$10,728	1.02	$10,685	$0	$10,685	$7,029	$10,728
23	51386	30	8	VC	1984	No Action	$0	$0	$1,623	1.02	$1,616	$0	$1,616	$1,119	$1,623
24	51462	170	8	VC	1980	No Action	$0	$0	$7,179	1.02	$7,150	$0	$7,150	$4,456	$7,179
25	5041025	65	8	VC	1987	No Action	$0	$0	$3,736	1.02	$3,721	$0	$3,721	$2,770	$3,736
	Total	4,250						$42,537	$109,085	3.05	$72,668	$42,537	$115,205	$102,715	$151,622

Table 5.24: Estimated asset values in year 2 (3-year investment plan)

(1) No.	(2) FSN	(3) Length (ft)	(4) Size (inch)	(5) Material	(6) Year	(7) M & R Alternative	(8) Unit Cost ($/LF)	(9) M & R Cost	(10) Base Value	(11) Rating	(12) Deteriorated Value	(13) Expected Added Value	(14) Deteriorated Value =(12)+(13)	(15) Book Value	(16) Modified Approach
1	51115	54	8	VC	1965	No Action	$0	$0	$684	1.02	$3,130	$0	$3,130	$3,378	$3,826
2	39249	78	8	VC	1962	No Action	$0	$0	$887	1.02	$4,521	$0	$4,521	$4,799	$5,426
3	57459	123	8	VC	1962	No Action	$0	$0	$1,399	1.02	$7,129	$0	$7,129	$7,567	$8,557
4	57966	143	8	VC	1962	No Action	$0	$0	$1,627	1.02	$8,288	$0	$8,288	$8,798	$9,948
5	14520	333	8	VC	1968	No Action	$0	$0	$5,017	1.02	$19,301	$0	$19,301	$21,367	$24,395
6	14783	16	8	VC	1968	Sliplining	$30	$473	$241	4.30	$42	$473	$515	$568	$714
7	58572	67	8	VC	1966	Sliplining	$30	$1,980	$891	4.30	$156	$1,980	$2,136	$2,302	$2,870
8	51488	117	8	VC	1966	Sliplining	$30	$3,457	$1,555	4.30	$273	$3,457	$3,730	$4,020	$5,012
9	51938	193	8	VC	1966	Sliplining	$30	$5,703	$2,566	4.30	$450	$5,703	$6,153	$6,631	$8,268
10	51507	298	8	VC	1966	Sliplining	$30	$8,805	$3,961	4.30	$695	$8,805	$9,500	$10,239	$12,766
11	59279	37	8	VC	1987	Grouting	$12	$0	$2,127	3.18	$965	$0	$965	$1,540	$2,127
12	51474	118	8	VC	1965	Grouting	$12	$0	$1,495	3.18	$679	$0	$679	$515	$1,495
13	51444	174	8	VC	1968	Grouting	$12	$0	$2,622	3.18	$1,190	$0	$1,190	$1,040	$2,622
14	19105	246	8	VC	1975	Grouting	$12	$0	$7,098	3.18	$3,223	$0	$3,223	$3,672	$7,098
15	58571	342	8	VC	1966	Grouting	$12	$0	$4,546	3.18	$2,064	$0	$2,064	$1,646	$4,546
16	18434	127	8	VC	1971	No Action	$0	$0	$2,619	2.13	$1,894	$0	$1,894	$1,174	$2,619
17	852	202	8	VC	1980	No Action	$0	$0	$8,530	2.13	$6,166	$0	$6,166	$5,147	$8,530
18	58769	268	8	VC	1973	No Action	$0	$0	$6,625	2.13	$4,789	$0	$4,789	$3,198	$6,625
19	58798	295	8	VC	1973	No Action	$0	$0	$7,292	2.13	$5,272	$0	$5,272	$3,521	$7,292
20	19261	351	8	VC	1979	No Action	$0	$0	$13,750	2.13	$9,940	$0	$9,940	$8,060	$13,750
21	212	188	8	VC	1985	No Action	$0	$0	$10,288	1.03	$10,203	$0	$10,203	$7,095	$10,288
22	44827	215	8	VC	1982	No Action	$0	$0	$10,728	1.03	$10,639	$0	$10,639	$6,844	$10,728
23	51386	30	8	VC	1984	No Action	$0	$0	$1,623	1.03	$1,609	$0	$1,609	$1,091	$1,623
24	51462	170	8	VC	1980	No Action	$0	$0	$7,179	1.03	$7,119	$0	$7,119	$4,332	$7,179
25	5041025	65	8	VC	1987	No Action	$0	$0	$3,736	1.03	$3,705	$0	$3,705	$2,705	$3,736
	Total	4,250						$20,417	$109,085	2.33	$113,442	$20,417	$133,859	$121,251	$172,039

Table 5.25: Estimated asset values in year 3 (3-year investment plan)

(1) No.	(2) FSN	(3) Length (ft)	(4) Size (inch)	(5) Material	(6) Year	(7) M & R Alternative	(8) Unit Cost ($/LF)	(9) M & R Cost	(10) Base Value	(11) Rating	(12) Deteriorated Value	(13) Expected Added Value	(14) Deteriorated Value =(12)+(13)	(15) Book Value	(16) Modified Approach
1	51115	54	8	VC	1965	No Action	$0	$0	$684	1.03	$3,116	$0	$3,116	$3,366	$3,826
2	39249	78	8	VC	1962	No Action	$0	$0	$887	1.03	$4,501	$0	$4,501	$4,784	$5,426
3	57459	123	8	VC	1962	No Action	$0	$0	$1,399	1.03	$7,098	$0	$7,098	$7,543	$8,557
4	57966	143	8	VC	1962	No Action	$0	$0	$1,627	1.03	$8,252	$0	$8,252	$8,770	$9,948
5	14520	333	8	VC	1968	No Action	$0	$0	$5,017	1.03	$19,217	$0	$19,217	$21,280	$24,395
6	14783	16	8	VC	1968	No Action	$0	$0	$241	1.02	$513	$0	$513	$564	$714
7	58572	67	8	VC	1966	No Action	$0	$0	$891	1.02	$2,127	$0	$2,127	$2,287	$2,870
8	51488	117	8	VC	1966	No Action	$0	$0	$1,555	1.02	$3,715	$0	$3,715	$3,993	$5,012
9	51938	193	8	VC	1966	No Action	$0	$0	$2,566	1.02	$6,128	$0	$6,128	$6,587	$8,268
10	51507	298	8	VC	1966	No Action	$0	$0	$3,961	1.02	$9,462	$0	$9,462	$10,171	$12,766
11	59279	37	8	VC	1987	Grouting	$12	$437	$2,127	3.31	$899	$388	$1,287	$1,941	$2,127
12	51474	118	8	VC	1965	Grouting	$12	$1,395	$1,495	3.31	$632	$1,237	$1,869	$1,884	$1,495
13	51444	174	8	VC	1968	Grouting	$12	$2,056	$2,622	3.31	$1,108	$1,824	$2,932	$3,051	$2,622
14	19105	246	8	VC	1975	Grouting	$12	$2,907	$7,098	3.31	$3,001	$2,579	$5,580	$6,457	$7,098
15	58571	342	8	VC	1966	Grouting	$12	$4,042	$4,546	3.31	$1,922	$3,585	$5,507	$5,610	$4,546
16	18434	127	8	VC	1971	No Action	$0	$0	$2,619	2.20	$1,859	$0	$1,859	$1,129	$2,619
17	852	202	8	VC	1980	No Action	$0	$0	$8,530	2.20	$6,055	$0	$6,055	$5,000	$8,530
18	58769	268	8	VC	1973	No Action	$0	$0	$6,625	2.20	$4,703	$0	$4,703	$3,084	$6,625
19	58798	295	8	VC	1973	No Action	$0	$0	$7,292	2.20	$5,177	$0	$5,177	$3,395	$7,292
20	19261	351	8	VC	1979	No Action	$0	$0	$13,750	2.20	$9,761	$0	$9,761	$7,823	$13,750
21	212	188	8	VC	1985	No Action	$0	$0	$10,288	1.05	$10,155	$0	$10,155	$6,918	$10,288
22	44827	215	8	VC	1982	No Action	$0	$0	$10,728	1.05	$10,589	$0	$10,589	$6,659	$10,728
23	51386	30	8	VC	1984	No Action	$0	$0	$1,623	1.05	$1,602	$0	$1,602	$1,063	$1,623
24	51462	170	8	VC	1980	No Action	$0	$0	$7,179	1.05	$7,086	$0	$7,086	$4,208	$7,179
25	5041025	65	8	VC	1987	No Action	$0	$0	$3,736	1.05	$3,688	$0	$3,688	$2,641	$3,736
	Total	4,250						$10,838	$109,085	1.72	$132,367	$9,613	$141,980	$130,208	$172,039

The changes in asset values over three years are shown in Figure 5.6. The amount of the increase in asset value is greater in the values estimated using the modified approach than the book value and the deteriorated value. During year 3, there is a gain in asset value for the deteriorated value and the book value from the investment for grouting. However, since grouting is considered as a preservation activity and an expense in the modified approach, no gain in asset value is observed in the modified approach.

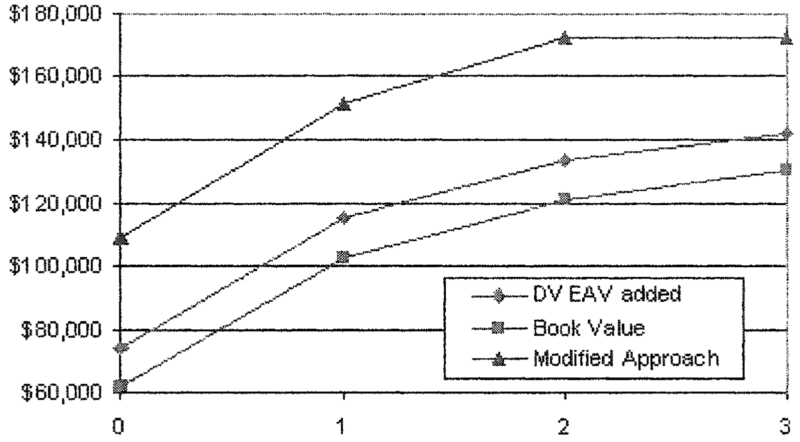


Figure 5.6: Changes in asset value (3 year plan)

5.3.2.5 Case 4: The Assets Are Repaired Over Five Years (Plan 1)

The 5-Year Investment Plan 1 assumes the provision of uniform funds over five years. Therefore, the required annual budget is $14,758. It is also assumed that the remainder of the annual budget was carried over to the next year for repair. The estimated asset values for year 1 and year 5, based on this investment plan are shown in Tables 5.26 and 5.27, and all of valuation processes for this investment are provided in Appendix D.

As shown in Table 5.26, two pipe segments in condition state 5 are replaced using pipe bursting, three pipe segments in condition state 4 are rehabilitated using sliplining, and one segment is grouted according to the available budget during year 1. As a result, the asset values estimated using the deteriorated value method, the depreciation method, and the modified approach are $86,646, $74,206, and $122,676 respectively. This process is repeated for the next four years to estimate the values of the considered pipe segments. As shown in Table 5.27, all pipe segments were repaired during the previous years, except segment 5 that requires $19,377 for pipe bursting. Therefore, no actions are needed for M & R after the five-year investments until the pipes reach condition state 3. The asset values after all M & R treatments are $139,752, $126,446, and $172,039 for the deteriorated value, the book value, and the modified approach-based value respectively.

Table 5.26: Estimated asset values in year 1 (5-year investment plan 1)

Available Fund = $14,758

(1) No.	(2) FSN	(3) Length	(4) Size	(5) Material	(6) Year	(7) M & R Alternative	(8) Unit Cost ($/LF)	(9) M & R Cost	(10) Base Value	(11) Rating	(12) Deteriorated Value	(13) Expected Added Value	(14) Deteriorated Value =(12)+(13)	(15) Book Value	(16) Modified Approach
1	51115	54	8	VC	1965	Pipe Bursting	$58	$3,142	$684	5	$0	$3,142	$3,142	$3,390	$3,826
2	39249	78	8	VC	1962	Pipe Bursting	$58	$4,539	$887	5	$0	$4,539	$4,539	$4,814	$5,426
3	57459	123	8	VC	1962	Pipe Bursting	$58	$0	$1,399	5	$0	$0	$0	$434	$1,399
4	57966	143	8	VC	1962	Pipe Bursting	$58	$0	$1,627	5	$0	$0	$0	$505	$1,627
5	14520	333	8	VC	1968	Pipe Bursting	$58	$0	$5,017	5	$0	$0	$0	$2,076	$5,017
6	14783	16	8	VC	1968	Sliplining	$30	$473	$241	4.14	$52	$473	$524	$573	$714
7	58572	67	8	VC	1966	Sliplining	$30	$1,980	$891	4.14	$191	$1,980	$2,171	$2,317	$2,870
8	51488	117	8	VC	1966	Sliplining	$30	$3,457	$1,555	4.14	$333	$3,457	$3,790	$4,047	$5,012
9	51938	193	8	VC	1966	Sliplining	$30	$0	$2,566	4.14	$550	$0	$550	$973	$2,566
10	51507	298	8	VC	1966	Sliplining	$30	$0	$3,961	4.14	$849	$0	$849	$1,503	$3,961
11	59279	37	8	VC	1987	Grouting	$12	$437	$2,127	3.05	$1,034	$388	$1,422	$2,014	$2,127
12	51474	118	8	VC	1965	Grouting	$12	$0	$1,495	3.05	$727	$0	$727	$541	$1,495
13	51444	174	8	VC	1968	Grouting	$12	$0	$2,622	3.05	$1,275	$0	$1,275	$1,085	$2,622
14	19105	246	8	VC	1975	Grouting	$12	$0	$7,098	3.05	$3,452	$0	$3,452	$3,794	$7,098
15	58571	342	8	VC	1966	Grouting	$12	$0	$4,546	3.05	$2,211	$0	$2,211	$1,724	$4,546
16	18434	127	8	VC	1971	No Action	$0	$0	$2,619	2.06	$1,928	$0	$1,928	$1,219	$2,619
17	852	202	8	VC	1980	No Action	$0	$0	$8,530	2.06	$6,279	$0	$6,279	$5,294	$8,530
18	58769	268	8	VC	1973	No Action	$0	$0	$6,625	2.06	$4,877	$0	$4,877	$3,313	$6,625
19	58798	295	8	VC	1973	No Action	$0	$0	$7,292	2.06	$5,368	$0	$5,368	$3,646	$7,292
20	19261	351	8	VC	1979	No Action	$0	$0	$13,750	2.06	$10,122	$0	$10,122	$8,297	$13,750
21	212	188	8	VC	1985	No Action	$0	$0	$10,288	1.02	$10,247	$0	$10,247	$7,273	$10,288
22	44827	215	8	VC	1982	No Action	$0	$0	$10,728	1.02	$10,685	$0	$10,685	$7,029	$10,728
23	51386	30	8	VC	1984	No Action	$0	$0	$1,623	1.02	$1,616	$0	$1,616	$1,119	$1,623
24	51462	170	8	VC	1980	No Action	$0	$0	$7,179	1.02	$7,150	$0	$7,150	$4,456	$7,179
25	5041025	65	8	VC	1987	No Action	$0	$0	$3,736	1.02	$3,721	$0	$3,721	$2,770	$3,736
	Total	4,250						$14,028	$109,085	3.05	$72,668		$86,646	$74,206	$122,676

Table 5.27: Estimated asset values in year 5 (5-year investment plan 1)

Available Fund = $19,377

(1) No.	(2) FSN	(3) Length	(4) Size	(5) Material	(6) Year	(7) M & R Alternative	(8) Unit Cost ($/LF)	(9) M & R Cost	(10) Base Value	(11) Rating	(12) Deteriorated Value	(13) Expected Added Value	(14) Deteriorated Value =(12)+(13)	(15) Book Value	(16) Modified Approach
1	51115	54	8	VC	1965	No Action	$0	$0	$684	1.07	$3,086	$0	$3,086	$3,343	$3,826
2	39249	78	8	VC	1962	No Action	$0	$0	$887	1.07	$4,458	$0	$4,458	$4,753	$5,426
3	57459	123	8	VC	1962	No Action	$0	$0	$1,399	1.05	$7,065	$0	$7,065	$7,495	$8,557
4	57966	143	8	VC	1962	No Action	$0	$0	$1,627	1.05	$8,214	$0	$8,214	$8,714	$9,948
5	14520	333	8	VC	1968	Pipe Bursting	$58	$19,377	$5,017	5	$0	$19,377	$19,377	$21,107	$24,395
6	14783	16	8	VC	1968	No Action	$0	$0	$241	1.07	$515	$0	$515	$556	$714
7	58572	67	8	VC	1966	No Action	$0	$0	$891	1.07	$2,132	$0	$2,132	$2,256	$2,870
8	51488	117	8	VC	1966	No Action	$0	$0	$1,555	1.07	$3,723	$0	$3,723	$3,940	$5,012
9	51938	193	8	VC	1966	No Action	$0	$0	$2,566	1.03	$6,017	$0	$6,017	$6,499	$8,268
10	51507	298	8	VC	1966	No Action	$0	$0	$3,961	1.03	$9,290	$0	$9,290	$10,034	$12,766
11	59279	37	8	VC	1987	No Action	$0	$0	$2,127	2.27	$1,328	$0	$1,328	$1,867	$2,127
12	51474	118	8	VC	1965	No Action	$0	$0	$1,495	2.06	$1,799	$0	$1,799	$1,833	$1,495
13	51444	174	8	VC	1968	No Action	$0	$0	$2,622	2.06	$2,814	$0	$2,814	$2,960	$2,622
14	19105	246	8	VC	1975	No Action	$0	$0	$7,098	2.06	$5,292	$0	$5,292	$6,212	$7,098
15	58571	342	8	VC	1966	No Action	$0	$0	$4,546	2.06	$5,296	$0	$5,296	$5,453	$4,546
16	18434	127	8	VC	1971	No Action	$0	$0	$2,619	2.35	$1,792	$0	$1,792	$1,039	$2,619
17	852	202	8	VC	1980	No Action	$0	$0	$8,530	2.35	$5,837	$0	$5,837	$4,706	$8,530
18	58769	268	8	VC	1973	No Action	$0	$0	$6,625	2.35	$4,533	$0	$4,533	$2,856	$6,625
19	58798	295	8	VC	1973	No Action	$0	$0	$7,292	2.35	$4,990	$0	$4,990	$3,143	$7,292
20	19261	351	8	VC	1979	No Action	$0	$0	$13,750	2.35	$9,409	$0	$9,409	$7,349	$13,750
21	212	188	8	VC	1985	No Action	$0	$0	$10,288	1.09	$10,052	$0	$10,052	$6,563	$10,288
22	44827	215	8	VC	1982	No Action	$0	$0	$10,728	1.09	$10,482	$0	$10,482	$6,289	$10,728
23	51386	30	8	VC	1984	No Action	$0	$0	$1,623	1.09	$1,585	$0	$1,585	$1,007	$1,623
24	51462	170	8	VC	1980	No Action	$0	$0	$7,179	1.09	$7,014	$0	$7,014	$3,961	$7,179
25	5041025	65	8	VC	1987	No Action	$0	$0	$3,736	1.09	$3,650	$0	$3,650	$2,512	$3,736
	Total	4,250						$19,377	$109,085	1.69	$120,375	$19,377	$139,752	$126,446	$172,039

Table 5.28 shows annual asset values based on the 5-Year Investment Plan 1 after the application of M & R treatments. After the five-year investment, the book value is 10% less than the deteriorated value, while the modified approach-based value is 23% greater than the deteriorated value. The annual losses and gains in asset values based on the 5-Year Investment Plan 1 are summarized in Table 5.29. The losses in deteriorated value vary due to the upgrades by application of M & R treatments and deterioration, but the losses in book value are constant throughout the five-year period. The gained value differences among the three values are due to the different computation procedures for the grouting activity. For instance, in year 4, only the grouting treatment was applied to four pipe segments in condition state 3. Therefore, the ETAVs and the M & R costs are added to the deteriorated value and the book value respectively, and no value is added to the modified approach-based value.

Table 5.28: Annual asset values (5-year investment plan 1)

Year	Deteriorated Value	Book Value		Modified Approach	
		Value	%	Value	%
1	$86,646	$74,206	86%	$122,676	142%
2	$100,628	$87,803	87%	$138,154	137%
3	$113,616	$100,430	88%	$152,662	134%
4	$121,485	$109,950	90%	$152,662	126%
5	$139,752	$126,446	90%	$172,039	123%

Table 5.29: Annual loss and gain in asset values (5-year investment plan 1)

Year	Deteriorated Value			Book Value			Modified Approach		
	Loss	Gain	Total	Loss	Gain	Total	Loss	Gain	Total
1	($1,244)	$13,978	$12,734	($1,881)	$14,028	$12,147	$0	$13,590	$13,590
2	($1,497)	$15,479	$13,981	($1,881)	$15,479	$13,598	$0	$15,479	$15,479
3	($1,520)	$14,508	$12,988	($1,881)	$14,508	$12,627	$0	$14,508	$14,508
4	($1,356)	$9,225	$7,869	($1,881)	$10,401	$8,520	$0	$0	$0
5	($1,110)	$19,377	$18,267	($1,881)	$19,377	$17,496	$0	$19,377	$19,377

This difference in valuation processes also affects the value of individual pipe segments. As shown in Figure 5.7, the estimated value of a segment using the deteriorated value method and the depreciation method increases in year 2 when the grouting treatment is applied and then decreases thereafter due to deterioration or depreciation. However, when the modified approach is used, no change in asset value occurs during the five-year investment period.

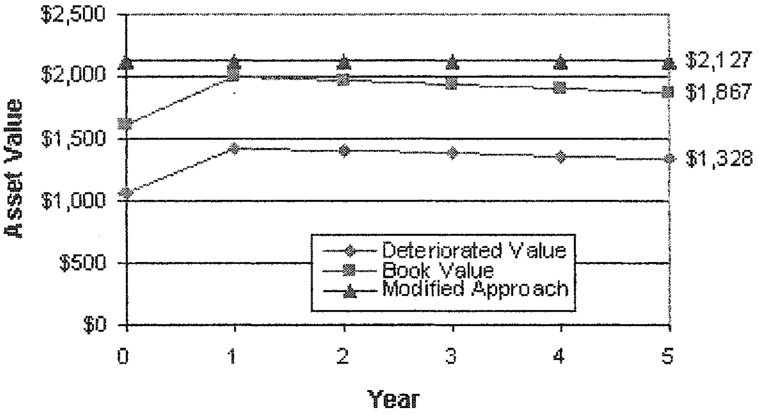


Figure 5.7: Asset value of FSN 59279 segment (5-year investment plan 1)

5.3.2.6 Case 5: The Assets Are Repaired Over Five Years (Plan 2)

Plan 2 requires more funding for the earlier years than the later years. In this case, it is assumed that 36%, 28%, 20%, 12%, and 4% of the entire required budget are the figures allocated during the five years. Therefore, the available budgets are $26,565, $20,662, $14,758, $8,855, and $2,952 for years 1, 2, 3, 4, and 5 respectively, as shown in Figure 5.8.

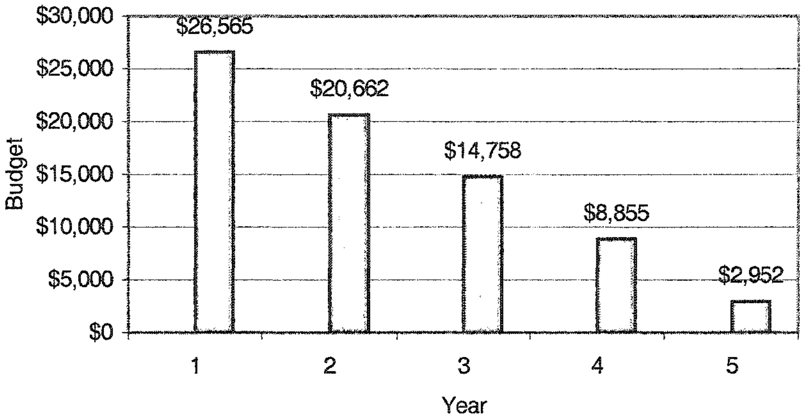


Figure 5.8: 5-year investment plan 2

The entire process for the estimation of asset values for the considered pipe segments based on the 5-Year Investment Plan 2 are presented in Appendix E. The annual estimated asset values are summarized in Table 5.30.

Table 5.30: Annual asset values (5-year investment plan 2)

Year	Deteriorated Value	Book Value		Modified Approach	
		Value	%	Value	%
1	$98,280	$85,790	87%	$134,697	137%
2	$116,217	$103,705	89%	$152,662	131%
3	$123,309	$110,831	90%	$152,662	124%
4	$122,182	$108,950	89%	$152,662	135%
5	$140,366	$126,446	90%	$172,039	123%

As shown in Table 5.30, the deteriorated values and the book values increase as M & R activities are performed. However, in year 4, the assets experience a decrease in value because no M & R treatment is applied due to the lack of sufficient funding and also from deterioration or depreciation. On the other hand, the modified approach-based value increases except in years 3 and 4 where only grouting or no treatment is applied.

The asset value changes due to M & R activities investments can be clearly seen when the annual losses and gains in asset value are identified, as shown in Table 5.31.

Table 5.31: Annual loss and gain in asset values (5-year investment plan 2)

Year	Deteriorated Value			Book Value			Modified Approach		
	Loss	Gain	Total	Loss	Gain	Total	Loss	Gain	Total
1	($1,244)	$25,612	$24,368	($1,881)	$25,612	$23,731	$0	$25,612	$25,612
2	($1,653)	$19,589	$17,936	($1,881)	$19,796	$17,916	$0	$17,965	$17,965
3	($896)	$7,988	$7,092	($1,881)	$9,006	$7,125	$0	$0	$0
4	($1,127)	$0	($1,127)	($1,881)	$0	($1,881)	$0	$0	$0
5	($1,193)	$19,377	$18,184	($1,881)	$19,377	$17,496	$0	$19,377	$19,377

There are losses in the deteriorated value and the book value in year 4. The modified approach-based value experiences no loss or gain in years 3 and 4. Depending on the application of grouting, the gain in asset value for the three methods begins to differ, and asset values in year 5 are $140,366, $126,466, and $172,039 for the deteriorated value, the book value, and the modified approach-based value respectively.

5.3.2.7 Case 6: The Assets Are Repaired Over Five Years (Plan 3)

The 5-Year Investment Plan 3 assumes the allocation of funds in the reverse order, i.e., less funding is allocated during the earlier years, and a larger portion of the budget is available during the later years, as shown in Figure 5.9.

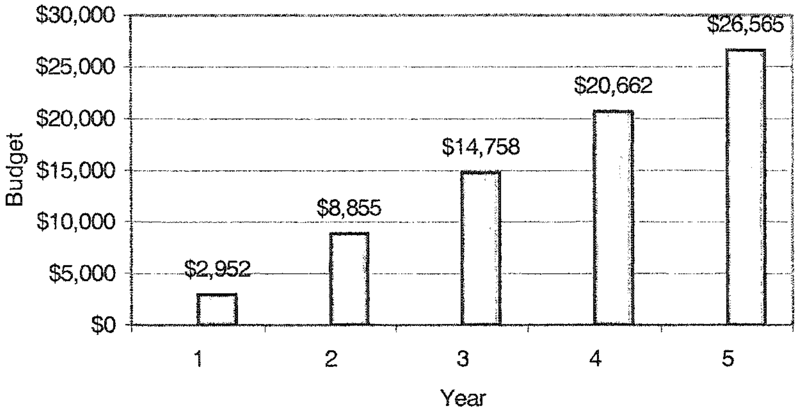


Figure 5.9: 5-year investment plan 3

The annual estimated asset values using the three valuation methods for this case are presented in Appendix F. In Table 5.32 the final annual asset values are shown, and in Table 5.33 the asset value losses and gains in asset values for the three valuation methods are given.

Table 5.32: Annual asset values (5-year investment plan 3)

Year	Deteriorated Value	Book Value		Modified Approach	
		Value	%	Value	%
1	$75,508	$63,068	84%	$111,538	148%
2	$81,677	$68,868	84%	$119,219	146%
3	$95,665	$82,466	86%	$134,697	141%
4	$113,545	$99,962	88%	$154,074	136%
5	$139,213	$126,446	91%	$172,039	124%

As shown in Table 5.32, the asset values increase during the five-year period as investments are made for M & R activities. Since the investments in the earlier years are small, the increases in asset value are smaller than those planned for later years. The estimated asset values in year 5 are $139,123, $126,446, and $172,039 for the deteriorated value, the book value, and the modified approach-based value respectively.

Table 5.33: Annual loss and gain in asset values (5-year investment plan 3)

Year	Deteriorated Value			Book Value			Modified Approach		
	Loss	Gain	Total	Loss	Gain	Total	Loss	Gain	Total
1	($1,244)	$2,840	$1,596	($1,881)	$2,890	$1,009	$0	$2,452	$2,452
2	($1,512)	$7,681	$6,169	($1,881)	$7,681	$5,800	$0	$7,681	$7,681
3	($1,491)	$15,479	$13,987	($1,881)	$15,479	$13,598	$0	$15,479	$15,479
4	($1,496)	$19,377	$17,881	($1,881)	$19,377	$17,496	$0	$19,377	$19,377
5	($1,522)	$27,190	$25,668	($1,881)	$28,365	$26,484	$0	$17,965	$17,965

Table 5.33 shows that the losses estimated using the depreciation method and the modified approach are constant at $1,881 and $0 per year. However, the losses in the deteriorated value change depending on the M & R treatments applied and the condition state changes after the treatments. Since grouting is applied to the pipe segments in condition state 3 during year 1 and 5, there are differences in the gains among the three asset values.

5.3.2.8 Impacts of Investment Plans on Asset Values

In the previous sections, the asset values of wastewater infrastructure assets were estimated using the three valuation methods based on different investments plans for M & R activities. The estimated asset values are summarized in Tables 5.34, 5.35, and 5.36 for the deteriorated value, the book value, and the modified approach-based value respectively.

Table 5.34: Estimated Deteriorated Values Based on Investment Plans

Investment Plans	Year					
	0	1	2	3	4	5
Base Year	$73,913	-	-	-	-	-
1-Year Plan	$73,913	$145,235	-	-	-	-
3-Year Plan	$73,913	$115,205	$133,859	$141,980	-	-
5-Year Plan 1	$73,913	$86,646	$100,628	$113,616	$121,485	$139,752
5-Year Plan 2	$73,913	$98,280	$116,217	$123,309	$122,182	$140,366
5-Year Plan 3	$73,913	$75,508	$81,677	$95,665	$113,545	$139,213

Table 5.35: Estimated Book Values Based on Investment Plans

Investment Plans	Year					
	0	1	2	3	4	5
Base Year	$62,059	-	-	-	-	-
1-Year Plan	$62,059	$133,969	-	-	-	-
3-Year Plan	$62,059	$102,715	$121,251	$130,208	-	-
5-Year Plan 1	$62,059	$74,206	$87,803	$100,430	$108,950	$126,446
5-Year Plan 2	$62,059	$85,790	$103,705	$110,831	$108,950	$126,446
5-Year Plan 3	$62,059	$63,068	$68,868	$82,446	$99,962	$126,446

Table 5.36: Estimated Modified Approach-Based Values Based on Investment Plans

Investment Plans	Year					
	0	1	2	3	4	5
Base Year	$109,085	-	-	-	-	-
1-Year Plan	$109,085	$172,039	-	-	-	-
3-Year Plan	$109,085	$151,622	$172,039	$172,039	-	-
5-Year Plan 1	$109,085	$122,676	$138,154	$152,662	$152,662	$172,039
5-Year Plan 2	$109,085	$134,697	$152,662	$152,662	$152,662	$172,039
5-Year Plan 3	$109,085	$111,538	$119,219	$134,697	$154,074	$172,039

As shown in Tables 5.34, 5.35, and 5.36, when using the modified approach, regardless of the investment periods, the asset value at the end of the period is $172,039, i.e., showing an increase of $62,954 for pipe bursting and sliplining from the base year value. Even though the same amount of money ($73,722) is invested for M & R treatments, the values estimated using the deteriorated value method and the depreciation method at the end of the investment period are different due to asset value losses arising from deterioration or depreciation.

The effects of delayed maintenance can be explained in terms of deteriorated value. As shown in Tables 5.34, 5.35, and 5.36, the asset values at the end of the five-year investment plans (plan 1, 2, and 3), based on the depreciation method and the modified approach, are the same. However, when the deteriorated value method is used, differences in asset values based on different investment plans can be detected. In Table 5.34, the deteriorated value in year 5 based on plan 2 (large investment in earlier years) is greater than the values obtained based on plan 1 (uniform investment) and plan 3 (large investment in later years). From these results, it can be concluded that a significant investment for M & R activities during the earlier years will maintain asset values at higher levels.

One of the advantages of the deteriorated value method is that since it uses condition ratings in the valuation process, the annual average condition rating of the wastewater infrastructure assets can be computed. As shown in Table 5.37, a large investment during the earlier years (5-year plan 2) enables the wastewater infrastructure assets to stay in the better condition states than those determined by the other investment plans (plan 1 and 3). Only the deteriorated value method can identify the different effort levels for the maintenance of wastewater infrastructure assets of municipalities in terms of monetary value. The 5-Year Investment Plan 3 produces the least asset value and the worst condition at the end of the investment period as shown in Tables 5.34 and 5.37. Therefore, when the deteriorated value method is used, the municipalities can determine the values of infrastructure assets incorporating deterioration of the assets and identify the conditions of the assets at the time of the valuation process.

Table 5.37: Estimated Average Condition Ratings Based on Investment Plans

Investment Plans	Year					
	0	1	2	3	4	5
Base Year	3.00	-	-	-	-	-
1-Year Plan	3.00	3.05	-	-	-	-
3-Year Plan	3.00	3.05	2.33	1.72	-	-
5-Year Plan 1	3.00	3.05	2.37	2.11	1.88	1.69
5-Year Plan 2	3.00	3.05	2.23	1.77	1.66	1.70
5-Year Plan 3	3.00	3.05	2.82	2.56	2.30	2.20

As a reference, the asset values estimated based on a 10-year investment plan ($7,379 per year) are presented in Appendix G. The estimated deteriorated value, the book value, and the modified approach-based value in year 10 are $131,896, $117,042, and $172,039 respectively.

5.4 Chapter Summary

This chapter presented the results of analyses for deterioration modeling and asset valuation for wastewater infrastructure assets in the City of San Diego. Deterioration models based on the nonlinear optimization-based approach and the ordered probit model-based approach were developed. The deterioration model obtained from the nonlinear optimization-based approach was selected and used for further analysis in this research. Using the deterioration model and associated transition probabilities, the LCCA determined the optimal M & R alternatives for wastewater infrastructure assets based on the dynamic programming optimization. For the selected 25 pipe segments in the City of San Diego, the deteriorated value method, the depreciation method, and the modified approach were applied to estimate the infrastructure asset values. The asset values showed substantial variations among the values obtained using different valuation methods. The difference between the asset values obtained using the modified approach and the depreciation method increases as pipe segments age. The pipes in poor condition states, such as condition states 4 and 5, show larger variations in asset values when the values estimated using the depreciation method and the modified approach are compared with the deteriorated value. Special attention is required in the selection of valuation method for infrastructure assets considering the substantial variations in asset values estimated from different valuation methods.

When different investment plans were applied, the deteriorated value method could detect the impacts of the investment plans, whereas the depreciation method and the modified approach did not capture the differences of the investment plans. The deteriorated value method can find the negative effects of delayed maintenance and demonstrate them in monetary values. The deteriorated value method is also capable of providing the conditions of infrastructure assets after M & R activities are applied.

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary of the Research

A valuation method based on the Markov chain process was developed in this study for the estimation of the value of wastewater infrastructure assets when deterioration is considered. As a first step, different methodologies were investigated to find a reliable deterioration model to be used as a foundation for the development of deterioration-based valuation model. Based on the developed deterioration model, a valuation method incorporating the condition states of the wastewater infrastructure assets was created. The developed deterioration-based valuation model was then applied for assessing the value of wastewater infrastructure assets and compared with the asset values estimated using other valuation methods, such as the depreciation method and the modified approach, which are recommended by Statement 34 of the Governmental Accounting Standards Board (GASB 34). For the life cycle cost analysis (LCCA), the dynamic programming technique was employed to determine the optimal maintenance and repair (M & R) alternatives among the considered seven alternatives. Based on the results of the LCCA, different investment scenarios were explored to investigate the impacts of the investment plan on asset values.

A Markov chain-based deterioration model was developed for the wastewater infrastructure assets in the City of San Diego. In order to estimate the transition probabilities of the Markov chain-based deterioration model, two different approaches were analyzed: the nonlinear optimization-based approach and the ordered probit model-based approach. The nonlinear optimization-based approach estimates the transition probabilities by minimizing the absolute distances between the expected condition ratings based on the Markov chain-based model and the average condition ratings obtained from the regression analysis using the condition rating data. A simple exponential distribution was found to be an appropriate regression model for the 8-inch (200 mm) vitrified clay (VC) pipes in the City of San Diego. However, it was noted that this approach has been criticized for not considering the relationship between the latent variable (deterioration) and the indicator variable (condition rating), and the ordinal scale of condition ratings. In addition, this approach requires several assumptions, such as the zoning concept and two nonzero values in a row of a transition matrix.

Therefore, in an attempt to find a better methodology for the development of the deterioration models for wastewater infrastructure assets, the ordered probit model in association with the incremental model was applied. The ordered probit model-based approach considers the relationship between the deterioration and the condition ratings and the ordinal scale of the condition ratings in the modeling process. This approach could estimate transition probabilities for individual pipe segments, grouped pipe segments, or the entire network. However, in spite of its theoretical and statistical advantages over the nonlinear optimization-based approach, the measurement of goodness-of-fit for the ordered probit model was low in some cases and the expected useful life was too short to be reasonable. Unsatisfactory outputs may have been due to the use of cross-sectional data rather than the use of panel data in the modeling process. It was concluded, therefore, that the nonlinear optimization-based approach was still a viable method for the development of the Markov chain-based deterioration model for the wastewater infrastructure assets in the City of San Diego and subsequently used in this study.

The deterioration-based valuation method (or deteriorated value method) was used for the estimation of current asset values based on the historical condition changes and future asset values by incorporating the expected added value that was derived from the concept of the rewards on Markov chain. The deteriorated value method could reflect the different levels of investments for M & R activities and estimate the future asset values in a probabilistic manner by incorporating the different transition probabilities for different types of M & R activities, such as routine maintenance, preservation, and improvement.

The values of wastewater infrastructure assets were then compared using the three valuation methods: the deteriorated value method, the depreciation method, and the modified approach, based on the optimal M & R alternatives obtained from the dynamic programming optimization. The asset values obtained using the depreciation method indirectly reflect the wear and tear of wastewater infrastructure assets by subtracting the calculated depreciation from the historical or replacement value. The book value obtained using the depreciation method approximates the loss of functionality based only on the age of the assets. The depreciation method does not reflect the actual changes in the physical and functional (loss of service) conditions in asset values. Therefore, when the depreciation method is used, assets of the same age but in different condition states have the same asset value. By the same token, assets of a different age but in the same condition state have different asset values even though they have a similar level of functionality.

The modified approach for asset valuation enables asset managers to monitor wastewater infrastructure assets in a proactive manner by applying the results of a condition assessment for future M & R activities. However, the asset values obtained from the modified approach do not reflect the deterioration of assets since neither deterioration nor depreciation is considered in the asset value in terms of loss. The asset value estimated by the modified approach only increases unless the assets are discarded, at which time the owners will experience a significant loss in the assets section of their financial reports. For instance, if infrastructure assets are lost due to natural disaster or intentional terror attacks, governmental agencies will experience substantial loss of assets in their financial report when the modified approach is used.

The deteriorated value method described in this study is capable of capturing the changes in conditions and the differences in the target levels of condition and investment plans. This method considers the impacts of different maintenance histories. For example, different levels of expenditures, schedules, and minimum acceptance levels will affect the value of the asset. As described in Chapter 5, the deteriorated value method could reflect the different types of investment plans over different periods in the valuation process. Depending on the minimum acceptance level for maintenance, the optimal M & R alternatives for wastewater infrastructure will be different. This difference can be detected in asset value when the deteriorated value method is used.

Substantial variations in asset values were found in this study depending on the valuation method selected. The book value was always less than the deteriorated value for all investment scenarios because the amount of depreciation was greater than the loss in value due to deterioration. The difference between the values obtained from the modified approach and other valuation methods increased as infrastructure assets aged, unless preservation activities were performed. Thus, employing the modified approach will cause an increase in the asset values on financial documents but the returns-on-investment will become smaller when revenues are evaluated by using the asset values as investments. The impacts of delayed M & R activities are identified in terms of monetary value when the deteriorated value method is used. However, this is not the case in other two valuation methods. The deteriorated value method also provides the expected condition ratings after the M & R alternatives are applied, which is useful information for making decisions regarding future investments for M & R activities.

The deteriorated value model described in this study requires more steps in the valuation process than the depreciation method and the modified approach. However, since the Markov chain-based model is commonly used in the deterioration prediction models of infrastructure assets and the developed valuation method is based on Markov chain processes, the deterioration-based valuation method can be readily incorporated in infrastructure management systems for the valuation of infrastructure assets.

Using the deteriorated value method, municipalities, auditors, and bond raters can determine the values of wastewater infrastructure assets more objectively by incorporating the impacts of deterioration on the value of the assets. When the deteriorated value method is used for the valuation of wastewater infrastructure assets, the development of deterioration models is a prerequisite. For municipalities, since the use of the deteriorated value method implies the systematic management of the assets including condition assessment, municipalities are required to allocate appropriate funds to perform condition assessment for their wastewater infrastructure assets. As the deteriorated value method enables asset managers to reflect the impacts of different investment plans for M & R activities in the values of infrastructure assets, municipalities will consider the asset values as a factor during their budgeting process.

The deteriorated value method allows the auditors to examine the financial reports of municipalities more easily. According to GASB 34, municipalities that employ the modified approach as their valuation method should disclose information regarding the condition of wastewater infrastructure assets in a separate report named "Required Supplementary Information (RSI)" (GASB 1999). However, when the deteriorated value method is used, the conditions of wastewater infrastructure assets are already incorporated in the values of the assets. Auditors reviewing the deteriorated values of wastewater infrastructure assets do not have to appraise other reports to evaluate the performance of municipalities based on the conditions of the assets.

Bond raters will also enjoy certain benefits when the deteriorated value method is used. The profitability of public agencies can be evaluated by estimating return-on-investments (ROIs) using the values of infrastructure assets as investment and the profits generated from infrastructure assets as return. The deteriorated value method provides bond raters with more accurate information about ROIs by reflecting the condition changes in the determination of asset values. As the deteriorated value method can recognize the negative effects of delayed maintenance, bond raters can evaluate the performance of municipalities regarding investments for M & R activities based on ROIs and reduced asset values using the deteriorated value method.

This method is also useful for the determination of infrastructure asset values for privatization. As indicated by Lowdon and Saldarriaga (2001), due to the increasing investment needs and the decreasing financial resources for M & R, the number of functions in infrastructure management operated by the private sector and the amount of funding provided by the private sector are increasing. The values of infrastructure assets are always of concern when the ownership of infrastructure assets is transferred from the public sector to the private sector or vice versa. The deteriorated value method can be used to estimate more accurate trading values of public facilities by incorporating the level of functionality in the asset values. Therefore, it is recommended that the valuation processes contained in GASB 34 be restructured to incorporate the deterioration of assets in the valuation processes.

6.2 Limitations of the Research

In this study a deterioration model was developed for wastewater infrastructure assets, and a deterioration-based valuation method was presented and compared with other valuation methods. However, there are several limitations in the application of the analysis results.

The deterioration model developed using the nonlinear optimization-based approach is applicable only for 8-inch (200 mm) VC pipes in the City of San Diego. Even though five different regression models were examined for four data groups, only one group showed good analysis results. When the ordered probit model-based approach was applied, the developed model was not satisfactory either. These problems may be alleviated when the data set includes other areas in the City of San Diego or is obtained from the periodic condition assessments.

In the optimization using the dynamic programming technique for the selection of optimal M & R alternatives, only construction costs were used for the optimization processes. Other costs, such as those resulting from traffic delays and disruptions, were not included in the analysis. In addition, other factors in the decision-making process, such as surrounding soil conditions, depth of installation, location of the pipe segments, and hydraulic capacity, can also assist in determining optimal solutions for future M & R investments.

The transition probabilities for preservation and improvement activities are assumed in this study. However, to obtain more accurate results from the analyses for optimal M & R treatments using the dynamic programming technique and for asset values using the deteriorated value method, it is desirable to use transition probabilities estimated from the actual condition assessment data rather than assumptions.

6.3 Contributions of the Research

This research made several contributions to the area of wastewater infrastructure asset management. The applicability of two different methods, the nonlinear optimization based approach and the ordered probit model-based approach, was investigated for the development of deterioration models for wastewater infrastructure assets. A valuation model for wastewater infrastructure assets considering deterioration was presented, variations in asset values estimated using different valuation methods were explored, and the impacts of investments for M & R treatments obtained from LCCA were investigated.

6.3.1 Contribution to the Body of Knowledge

A valuation method was presented in this study for wastewater infrastructure assets that estimates the values of wastewater infrastructure assets based solely on the condition states of the assets. This method incorporates the wear and tear from the usage of the facilities in asset values, which is not considered in the modified approach. This method also reflects the condition changes from the measurement or prediction (or deterioration) model in terms of loss in asset value, while the depreciation method uses constant depreciation based only on the age of the assets as the loss in asset values, regardless of the functionality of the assets.

This study can provides methodologies to evaluate the effects of the different investment patterns for M & R activities in monetary terms. When the deteriorated value method is used for the valuation of infrastructure assets, the differences in the asset values at the end of an investment period can be detected. The negative effects of delayed maintenance can be captured in terms of reduced asset values.

In this study the applicability of two different approaches for the development of deterioration models for wastewater infrastructure assets is investigated. The nonlinear optimization-based approach requires several assumptions in the modeling process to produce reasonable deterioration models. The ordered probit model-based approach provides a sound platform for deterioration modeling theoretically and statistically. It was identified that even though the ordered probit model-based approach has advantages over the nonlinear optimization-based approach, it may not be applicable until sufficient condition data of wastewater infrastructure assets are accumulated over time.

6.3.2 Contribution to the Body of Practice

The deteriorated value method developed in this study can be readily used for the valuation of wastewater infrastructure assets if the condition ratings of the assets are available. This study provides a step-by-step approach for the valuation of infrastructure assets when different M & R activities are performed. Using the deteriorated value method, municipalities can determine the values of their wastewater infrastructure assets reflecting the condition of the assets.

The procedures for the development of deterioration models for wastewater infrastructure assets based on the ordered probit model are described in this study. The variables, such as diameter of pipe, length of sewer runs, type of pipe material, and slope of sewer runs, that can be used for the deterioration models are also identified. The average individual procedure can be applied to estimate transition probabilities for Markov Chain-based deterioration models for individual sewer runs, groups of sewer runs, or entire sewer network in a city.

The life cycle cost analysis based on the dynamic programming recommends appropriate M & R alternatives for the pipes in each condition state. Using the results of LCCA, asset managers of municipalities can determine the required budget for M & R activities. When the deteriorated value method is used, the values of infrastructure assets after the application of M & R treatments recommended by LCCA can be estimated.

6.4 Recommendations for Further Research

Deterioration modeling, LCCA, and valuation methods for wastewater infrastructure assets were studied in this study. While sound methodologies were identified that can be used in the area of wastewater infrastructure asset management, research is needed to reduce the uncertainties in the analyses in the development of deterioration models and valuation processes. The following issues can be potentially studied in the future.

1. Guidelines for the Integration of Data for Wastewater Infrastructure Assets

As wastewater infrastructure assets age, and the perception of the importance of systematic infrastructure asset management increases, the need for sound mathematical models for deterioration, valuation, and LCCA also increases. Since successful modeling results are dependent on the availability and integrity of the data used, the collection and management of good data are crucial. However, unlike other infrastructure assets such as pavements and bridges, municipalities owning wastewater infrastructure assets do not have sufficient historical data for the production of accurate results from the analyses. Therefore, there is a need to develop a set of guidelines for the collection and management of data for wastewater infrastructure assets, which may include the current practices of municipalities in data collection, the identification of factors that can affect deterioration and decision-making for investment planning, the measurement methods of the factors, the best data format for storage and future utilization, etc. Possible factors for further analyses can include the size of the pipe, the depth of the installation, the pipe material, the slope, the soil condition, the ground water level, the condition rating, the age, and the cost.

Collecting information regarding M & R activities and the performance of facilities after M & R treatments is also needed. Deterioration models without M & R activities can be identified by using this information as well as the effects of M & R activities on deterioration. When Markov chain-based deterioration models are developed for M & R activities, the transition probabilities obtained from the deterioration models can be useful for planning the future investment for M & R activities using LCCA.

Further work can also include investigating the reduction and correction of measurement errors in condition ratings. Since a condition assessment of wastewater infrastructure assets is mainly based on closed circuit TV (CCTV) inspection and the subjective rating of inspectors, these data have a high possibility for errors. Therefore, possible issues for future research could be the identification of the factors that can induce errors and possible solutions, the development of a multi-media educational tool (web-based or CD-ROM version movie clips for various defects) to reduce the subjectivity in condition rating, and the development of mathematical models to correct the measurement errors.

2. Standardized Condition Rating System

A condition rating system is required to determine the current conditions and predict the future conditions of infrastructure assets. Without a condition rating system, it is difficult to evaluate current management practices and plan future investments to ensure better performance of the facilities and provision of stable services to the residents of the community. Pavement systems and bridge systems have standardized condition rating systems, i.e., Pavement Condition Index (PCI) (Carnahan et al. 1987) and concrete bridge deck condition ratings (FHWA 1979). However, each municipality develops a different rating system for its wastewater infrastructure assets as described in Chapter 2. The use of different condition rating systems prevents objective comparison of the maintenance effects of wastewater infrastructure assets and information-sharing regarding condition assessment among municipalities. Therefore, a standardized condition rating system needs to be developed for wastewater infrastructure assets. This standardized rating system should be extensive so that municipalities could use it by simply removing or adding a few items, thereby, developing a modified rating system for their own purposes and minimizing differences among municipalities.

In recent years municipalities have begun to develop condition rating systems. Hence, it is timely to develop a standardized rating system in the near future to avoid redundant work and cost investments for converting the existing data and updating the missing data. The development of a standardized condition rating system could include the investigation of condition rating systems currently used by the municipalities, identification of an appropriate number of condition levels in the rating system, identification of defects and level of damages to be used as the rating criteria, and establishment of a scoring system for each criterion.

3. Application of the Deteriorated Value Method for Other Infrastructure Systems

A valuation method considering the deterioration of assets in the process was developed in this study. Even though this method was developed for wastewater infrastructure assets, it can be applied to other infrastructure assets, such as pavement, and bridge systems. The variables in the deterioration model, the expected useful life, and applicable M & R activities will vary depending on the type of assets and will result in diverse patterns in deterioration model and transition probabilities. Therefore, the asset values of other infrastructure assets will have different patterns.

Research activities for the application of the deteriorated value method may include the development of deterioration models based on the Markov chain process, the selection of optimal M & R alternatives using the optimization technique, the classification of M & R alternatives for preservation and improvement activities, the development of future investment plans based on optimal M & R alternatives, and the investigation of variations in asset values using the valuation methods.

4. Enhancements to the Deterioration-Based Valuation Model

The deterioration-based valuation model developed in this study determines the values of infrastructure assets using conditions of the assets and the investments for M & R activities recommended by LCCA. The valuation of infrastructure assets is a component of infrastructure asset management system. When an integrated wastewater infrastructure asset management system, which includes condition assessment, deterioration modeling, investment planning, demand forecasting, and vulnerability assessment, is developed, the impacts of variations of other components in the management system on asset values can be identified and appropriate decisions can be made to minimize the negative impacts on infrastructure asset values. When the integrated wastewater asset management system is developed, it should be a computer-based system so that the changes in one component can be automatically reflected in other components. For instance, the changes in asset value due to M & R activities should be linked to the changes in conditions of assets. By the same token, the changes in conditions due to deterioration should be reflected in the values of wastewater infrastructure assets. For vulnerability assessment of infrastructure assets to disaster or intentional attacks, the deteriorated value of infrastructure asset can be used as a basis for benefit cost analysis for developing appropriate mitigation strategies. For instance, when decisions are made between new construction and retrofitting existing infrastructure assets to minimize the vulnerability of these assets, the deteriorated value method can provide information regarding benefits and costs for new construction and retrofitting in terms of asset values incorporating deterioration of infrastructure assets.

LIST OF REFERENCES

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APPENDICES

Appendix A: Results of Regression Analysis

Table A.1: Summary of regression analysis for 6-inch (150 mm) VC pipes

Coefficient	Value	P-value	Remarks
$Conditoin\ Rating = \beta_0 + \beta_1 AGE + \beta_2 AGE^2$			
R^2	0.049869		Low R^2 High Intercept High P-values
β_0	3.062564	0.1443	
β_1	-0.064631	0.5855	
β_2	0.001420	0.3725	
$Condition\ Rating = \beta_0 + \beta_1 AGE + \beta_2 AGE^2 + \beta_3 AGE^3$			
R^2	0.051088		Low R^2 High Intercept High P-values
β_0	6.808151	0.4545	
β_1	-0.463383	0.6257	
β_2	0.014063	0.6384	
β_3	-0.000124	0.6722	
$Condition\ Rating = \exp(\beta_0 + \beta_1 AGE)$			
R^2	0.087611		Low R^2 High P-value
β_0	0.147879	0.5608	
β_1	0.019937	0.0003	
$Condition\ Rating = \exp(\beta_0 + \beta_1 AGE + \beta_2 AGE^2)$			
R^2	0.104575		Low R^2 High Intercept (3.5) High P-values
β_0	1.241973	0.0847	
β_1	-0.045733	0.2612	
β_2	0.000889	0.1044	
$Condition\ Rating = \exp(\beta_0 + \beta_1 AGE + \beta_2 AGE^2 + \beta_3 AGE^3)$			
R^2	0.110727		Low R^2 High intercept (67.6) High P-values
β_0	4.214031	0.1767	
β_1	-0.362136	0.2657	
β_2	0.010921	0.2866	
β_3	-0.000098	0.3268	

Table A.2: Summary of regression analysis for 10-inch (250 mm) VC pipes

Coefficient	Value	P-value	Remarks
$Conditoin\ Rating = \beta_0 + \beta_1 AGE + \beta_2 AGE^2$			
R^2	0.294266		High Intercept High P-values
β_0	12.110708	0.0231	
β_1	-0.601541	0.0467	
β_2	0.008794	0.0310	
$Condition\ Rating = \beta_0 + \beta_1 AGE + \beta_2 AGE^2 + \beta_3 AGE^3$			
R^2	0.346943		High Intercept High P-values
β_0	-15.608195	0.4634	
β_1	2.003231	0.3108	
β_2	-0.068936	0.2403	
β_3	0.000738	0.1864	
$Condition\ Rating = \exp(\beta_0 + \beta_1 AGE)$			
R^2	0.192737		High P-value
β_0	0.025876	0.9512	
β_1	0.023964	0.0220	
$Condition\ Rating = \exp(\beta_0 + \beta_1 AGE + \beta_2 AGE^2)$			
R^2	0.408751		High Intercept (161.1) High P-values
β_0	5.082243	0.0077	
β_1	-0.272261	0.0122	
β_2	0.003977	0.0068	
$Condition\ Rating = \exp(\beta_0 + \beta_1 AGE + \beta_2 AGE^2 + \beta_3 AGE^3)$			
R^2	0.415767		High intercept (3.4) High P-values
β_0	1.214281	0.8740	
β_1	0.091216	0.8973	
β_2	-0.006869	0.7428	
β_3	0.000103	0.6042	

Table A.3: Summary of regression analysis for 8-inch (200 mm) PVC pipes

Coefficient	Value	P-value	Remarks
$Conditoin\ Rating = \beta_0 + \beta_1 AGE + \beta_2 AGE^2$			
R^2	0.398916		High Intercept
β_0	2.616008	<0.0001	
β_1	-0.128179	0.0027	
β_2	0.002793	0.0002	
$Condition\ Rating = \beta_0 + \beta_1 AGE + \beta_2 AGE^2 + \beta_3 AGE^3$			
R^2	0.511941		Low Intercept High P-values
β_0	0.076320	0.9365	
β_1	0.221934	0.0672	
β_2	-0.011248	0.0174	
β_3	0.000165	0.0033	
$Condition\ Rating = \exp(\beta_0 + \beta_1 AGE)$			
R^2	0.095163		Low R^2 High P-values
β_0	-0.079204	0.6160	
β_1	0.013169	0.0370	
$Condition\ Rating = \exp(\beta_0 + \beta_1 AGE + \beta_2 AGE^2)$			
R^2	0.300618		High Intercept (2.5)
β_0	0.931113	0.0053	
β_1	-0.068216	0.0059	
β_2	0.001418	0.0009	
$Condition\ Rating = \exp(\beta_0 + \beta_1 AGE + \beta_2 AGE^2 + \beta_3 AGE^3)$			
R^2	0.427698		High P-values
β_0	-0.527163	0.3507	
β_1	0.132818	0.0620	
β_2	-0.006644	0.0167	
β_3	0.000095	0.0039	

Appendix B: Estimated Transition Probabilities based on Ordered Probit Model

Table B.1: Estimated transition probabilities based on ordered probit model

Age	P_{11}	P_{12}	P_{13}	P_{14}	P_{15}	P_{22}	P_{23}	P_{24}	P_{25}	P_{33}	P_{34}	P_{35}	P_{44}	P_{45}
0	0.967	0.031	0.002	0.000	0.000	0.870	0.091	0.028	0.012	0.849	0.112	0.039	0.446	0.554
1	0.961	0.036	0.003	0.000	0.000	0.862	0.096	0.030	0.013	0.842	0.117	0.041	0.446	0.554
2	0.955	0.041	0.003	0.000	0.000	0.853	0.101	0.032	0.014	0.834	0.121	0.044	0.446	0.554
3	0.948	0.047	0.004	0.001	0.000	0.844	0.106	0.035	0.015	0.827	0.126	0.047	0.446	0.554
4	0.940	0.054	0.005	0.001	0.000	0.835	0.111	0.037	0.017	0.819	0.131	0.050	0.446	0.554
5	0.931	0.062	0.006	0.001	0.000	0.825	0.117	0.040	0.018	0.811	0.136	0.053	0.446	0.554
6	0.921	0.070	0.007	0.001	0.000	0.815	0.123	0.043	0.020	0.803	0.141	0.056	0.446	0.554
7	0.911	0.079	0.009	0.001	0.000	0.804	0.128	0.046	0.022	0.794	0.146	0.060	0.446	0.554
8	0.899	0.089	0.010	0.002	0.000	0.793	0.134	0.049	0.024	0.786	0.151	0.064	0.446	0.554
9	0.886	0.099	0.012	0.002	0.000	0.782	0.140	0.052	0.026	0.777	0.156	0.067	0.446	0.554
10	0.872	0.111	0.014	0.003	0.001	0.771	0.146	0.055	0.028	0.768	0.161	0.071	0.446	0.554
11	0.856	0.123	0.017	0.003	0.001	0.759	0.152	0.059	0.031	0.759	0.166	0.076	0.446	0.554
12	0.840	0.135	0.020	0.004	0.001	0.746	0.158	0.063	0.033	0.749	0.171	0.080	0.446	0.554
13	0.822	0.149	0.023	0.005	0.001	0.734	0.164	0.066	0.036	0.739	0.176	0.084	0.446	0.554
14	0.803	0.163	0.027	0.006	0.001	0.721	0.170	0.070	0.039	0.730	0.181	0.089	0.446	0.554
15	0.783	0.177	0.031	0.007	0.002	0.708	0.176	0.074	0.042	0.720	0.186	0.094	0.446	0.554
16	0.762	0.192	0.035	0.009	0.002	0.694	0.182	0.079	0.046	0.709	0.192	0.099	0.446	0.554
17	0.740	0.207	0.040	0.010	0.003	0.680	0.187	0.083	0.049	0.699	0.197	0.105	0.446	0.554
18	0.717	0.222	0.046	0.012	0.004	0.666	0.193	0.087	0.053	0.688	0.202	0.110	0.446	0.554
19	0.692	0.237	0.052	0.014	0.004	0.652	0.199	0.092	0.057	0.678	0.207	0.116	0.446	0.554
20	0.667	0.253	0.058	0.017	0.005	0.637	0.204	0.097	0.062	0.667	0.211	0.122	0.446	0.554
21	0.641	0.268	0.065	0.019	0.007	0.623	0.210	0.101	0.066	0.656	0.216	0.128	0.446	0.554
22	0.615	0.282	0.073	0.023	0.008	0.608	0.215	0.106	0.071	0.645	0.221	0.134	0.446	0.554
23	0.588	0.296	0.081	0.026	0.010	0.593	0.220	0.111	0.077	0.633	0.226	0.141	0.446	0.554
24	0.560	0.310	0.089	0.030	0.011	0.577	0.224	0.116	0.082	0.622	0.230	0.148	0.446	0.554
25	0.532	0.322	0.098	0.034	0.014	0.562	0.229	0.121	0.088	0.610	0.235	0.155	0.446	0.554

Table B.1(Continued)

Age	P_{11}	P_{12}	P_{13}	P_{14}	P_{15}	P_{22}	P_{23}	P_{24}	P_{25}	P_{33}	P_{34}	P_{35}	P_{44}	P_{45}
26	0.504	0.333	0.107	0.039	0.016	0.546	0.233	0.126	0.094	0.599	0.239	0.162	0.446	0.554
27	0.476	0.344	0.117	0.044	0.019	0.531	0.237	0.131	0.101	0.587	0.243	0.169	0.446	0.554
28	0.448	0.353	0.126	0.050	0.023	0.515	0.241	0.136	0.108	0.575	0.247	0.177	0.446	0.554
29	0.420	0.360	0.136	0.056	0.027	0.499	0.244	0.142	0.115	0.564	0.251	0.185	0.446	0.554
30	0.393	0.366	0.147	0.063	0.032	0.484	0.247	0.147	0.123	0.552	0.255	0.193	0.446	0.554
31	0.366	0.370	0.157	0.070	0.037	0.468	0.250	0.152	0.131	0.540	0.259	0.202	0.446	0.554
32	0.340	0.373	0.167	0.077	0.043	0.452	0.252	0.157	0.139	0.528	0.262	0.210	0.446	0.554
33	0.315	0.374	0.176	0.085	0.050	0.437	0.254	0.162	0.148	0.516	0.265	0.219	0.446	0.554
34	0.290	0.373	0.186	0.093	0.057	0.421	0.256	0.167	0.157	0.504	0.268	0.228	0.446	0.554
35	0.267	0.371	0.195	0.102	0.066	0.406	0.257	0.171	0.166	0.492	0.271	0.237	0.446	0.554
36	0.244	0.367	0.203	0.110	0.075	0.391	0.258	0.176	0.176	0.480	0.274	0.246	0.446	0.554
37	0.222	0.361	0.211	0.119	0.086	0.376	0.258	0.180	0.186	0.468	0.276	0.256	0.446	0.554
38	0.202	0.354	0.218	0.128	0.097	0.361	0.258	0.185	0.196	0.456	0.278	0.266	0.446	0.554
39	0.183	0.346	0.224	0.137	0.110	0.346	0.258	0.189	0.207	0.444	0.280	0.276	0.446	0.554
40	0.165	0.336	0.230	0.146	0.124	0.331	0.257	0.193	0.218	0.432	0.282	0.286	0.446	0.554
41	0.148	0.324	0.234	0.155	0.139	0.317	0.256	0.197	0.230	0.420	0.284	0.296	0.446	0.554
42	0.132	0.312	0.237	0.164	0.155	0.303	0.255	0.200	0.242	0.408	0.285	0.307	0.446	0.554
43	0.118	0.299	0.240	0.172	0.172	0.290	0.253	0.203	0.254	0.397	0.286	0.317	0.446	0.554
44	0.104	0.285	0.241	0.179	0.191	0.276	0.251	0.206	0.267	0.385	0.287	0.328	0.446	0.554
45	0.092	0.271	0.241	0.187	0.210	0.263	0.248	0.209	0.280	0.374	0.287	0.339	0.446	0.554
46	0.081	0.256	0.239	0.193	0.231	0.250	0.245	0.212	0.293	0.362	0.288	0.350	0.446	0.554
47	0.071	0.240	0.237	0.199	0.253	0.238	0.242	0.214	0.306	0.351	0.288	0.361	0.446	0.554
48	0.062	0.225	0.233	0.204	0.276	0.226	0.238	0.216	0.320	0.340	0.287	0.373	0.446	0.554
49	0.054	0.210	0.229	0.208	0.300	0.214	0.235	0.217	0.334	0.329	0.287	0.384	0.446	0.554
50	0.046	0.194	0.223	0.211	0.325	0.203	0.230	0.218	0.349	0.318	0.286	0.396	0.446	0.554

Table B.1(Continued)

Age	P_{11}	P_{12}	P_{13}	P_{14}	P_{15}	P_{22}	P_{23}	P_{24}	P_{25}	P_{33}	P_{34}	P_{35}	P_{44}	P_{45}
51	0.040	0.180	0.217	0.213	0.350	0.192	0.226	0.219	0.363	0.308	0.285	0.407	0.446	0.554
52	0.034	0.165	0.209	0.215	0.377	0.181	0.221	0.220	0.378	0.297	0.284	0.419	0.446	0.554
53	0.029	0.151	0.201	0.215	0.404	0.171	0.216	0.220	0.393	0.287	0.283	0.431	0.446	0.554
54	0.025	0.137	0.193	0.214	0.431	0.161	0.211	0.220	0.408	0.276	0.281	0.443	0.446	0.554
55	0.021	0.125	0.184	0.212	0.459	0.151	0.206	0.220	0.423	0.266	0.279	0.454	0.446	0.554
56	0.018	0.112	0.174	0.209	0.487	0.142	0.200	0.219	0.439	0.257	0.277	0.466	0.446	0.554
57	0.015	0.101	0.164	0.205	0.515	0.133	0.195	0.218	0.454	0.247	0.275	0.478	0.446	0.554
58	0.012	0.090	0.154	0.200	0.543	0.125	0.189	0.216	0.470	0.238	0.272	0.490	0.446	0.554
59	0.010	0.080	0.144	0.195	0.571	0.117	0.183	0.214	0.486	0.228	0.269	0.502	0.446	0.554
60	0.008	0.071	0.134	0.188	0.598	0.109	0.177	0.212	0.501	0.219	0.266	0.514	0.446	0.554
61	0.007	0.063	0.124	0.181	0.625	0.102	0.171	0.210	0.517	0.210	0.263	0.526	0.446	0.554
62	0.006	0.055	0.114	0.174	0.652	0.095	0.165	0.207	0.533	0.202	0.260	0.538	0.446	0.554
63	0.005	0.048	0.105	0.165	0.677	0.088	0.159	0.204	0.548	0.193	0.256	0.550	0.446	0.554
64	0.004	0.042	0.095	0.157	0.702	0.082	0.153	0.201	0.564	0.185	0.252	0.562	0.446	0.554
65	0.003	0.036	0.087	0.148	0.726	0.076	0.146	0.198	0.579	0.177	0.249	0.574	0.446	0.554
66	0.002	0.031	0.078	0.139	0.749	0.071	0.140	0.194	0.595	0.170	0.244	0.586	0.446	0.554
67	0.002	0.027	0.070	0.130	0.771	0.066	0.134	0.190	0.610	0.162	0.240	0.598	0.446	0.554
68	0.002	0.023	0.063	0.121	0.792	0.061	0.128	0.186	0.625	0.155	0.236	0.609	0.446	0.554
69	0.001	0.019	0.056	0.112	0.811	0.056	0.122	0.182	0.640	0.148	0.232	0.621	0.446	0.554
70	0.001	0.016	0.050	0.103	0.830	0.052	0.117	0.177	0.655	0.141	0.227	0.632	0.446	0.554

Appendix C: Results of Life Cycle Cost Analysis using Dynamic Programming

Table C.1: Results of optimization using dynamic programming

Analysis Period (n)	Condition State (i)	$f_n(i)=\min\limits_{a}\{C_n(i,a)+\alpha\sum\limits_{j=1}^{5}p(j\mid i,a,n)f_{n-1}(i)\}$							$f_n(i)$	a
		NA	RC	GR	CIPP	SL	PB	OR		
1	1	$0	$6	$12	$59	$30	$58	$83	$0	NA
	2	$1	$7	$12	$59	$30	$58	$83	$1	NA
	3			$13	$59	$30	$58	$83	$13	GR
	4				$59	$30	$58	$83	$30	SL
	5						$58	$83	$58	PB
2	1	$0	$6	$12	$59	$30	$58	$83	$0	NA
	2	$3	$9	$12	$59	$30	$58	$83	$3	NA
	3			$14	$59	$30	$58	$83	$14	GR
	4				$59	$30	$58	$83	$30	SL
	5						$58	$83	$58	PB
3	1	$0	$6	$12	$59	$30	$58	$83	$0	NA
	2	$4	$10	$12	$59	$30	$58	$83	$4	NA
	3			$16	$59	$30	$58	$83	$16	GR
	4				$59	$30	$58	$83	$30	SL
	5						$58	$83	$58	PB
4	1	$0	$6	$12	$59	$30	$58	$83	$0	NA
	2	$5	$11	$12	$59	$30	$58	$83	$5	NA
	3			$17	$59	$30	$58	$83	$17	GR
	4				$59	$30	$58	$83	$30	SL
	5						$58	$83	$58	PB
5	1	$0	$6	$12	$59	$30	$58	$83	$0	NA
	2	$7	$13	$12	$59	$30	$58	$83	$7	NA
	3			$18	$59	$30	$58	$83	$18	GR
	4				$59	$30	$58	$83	$30	SL
	5						$58	$83	$58	PB
6	1	$0	$6	$12	$59	$30	$58	$83	$0	NA
	2	$8	$14	$12	$59	$30	$58	$83	$8	NA
	3			$20	$59	$30	$58	$83	$20	GR
	4				$59	$30	$58	$83	$30	SL
	5						$58	$83	$58	PB
7	1	$0	$6	$12	$59	$30	$59	$83	$0	NA
	2	$9	$15	$12	$59	$30	$59	$83	$9	NA
	3			$21	$59	$30	$59	$83	$21	GR
	4				$59	$30	$59	$83	$30	SL
	5						$59	$83	$59	PB
8	1	$1	$6	$12	$60	$30	$59	$83	$1	NA
	2	$10	$16	$12	$60	$30	$59	$83	$10	NA
	3			$22	$60	$30	$59	$83	$22	GR
	4				$60	$30	$59	$83	$30	SL
	5						$59	$83	$59	PB

Table C.1(Continued)

Analysis Period (n)	Condition State (i)	$f_n(i) = \min_a \{C_n(i,a) + \alpha \sum_{j=1}^{5} p(j \mid i,a,n) f_{n-1}(i)\}$							$f_n(i)$	a
		NA	RC	GR	CIPP	SL	PB	OR		
9	1	$1	$7	$13	$60	$30	$59	$83	$1	NA
	2	$11	$17	$13	$60	$30	$59	$83	$11	NA
	3			$23	$60	$30	$59	$83	$23	GR
	4				$60	$30	$59	$83	$30	SL
	5						$59	$83	$59	PB
10	1	$1	$7	$13	$60	$30	$59	$83	$1	NA
	2	$12	$18	$13	$60	$30	$59	$83	$12	NA
	3			$24	$60	$30	$59	$83	$24	GR
	4				$60	$30	$59	$83	$30	SL
	5						$59	$83	$59	PB
11	1	$1	$7	$13	$60	$30	$59	$84	$1	NA
	2	$13	$19	$13	$60	$30	$59	$84	$13	GR
	3			$25	$60	$30	$59	$84	$25	GR
	4				$60	$30	$59	$84	$30	SL
	5						$59	$84	$59	PB
12	1	$1	$7	$13	$60	$31	$59	$84	$1	NA
	2	$14	$20	$13	$60	$31	$59	$84	$13	GR
	3			$26	$60	$31	$59	$84	$26	GR
	4				$60	$31	$59	$84	$31	SL
	5						$59	$84	$59	PB
13	1	$1	$7	$13	$60	$31	$59	$84	$1	NA
	2	$14	$20	$13	$60	$31	$59	$84	$13	GR
	3			$26	$60	$31	$59	$84	$26	GR
	4				$60	$31	$59	$84	$31	SL
	5						$59	$84	$59	PB
14	1	$2	$8	$13	$60	$31	$60	$84	$2	NA
	2	$14	$20	$13	$60	$31	$60	$84	$13	GR
	3			$26	$60	$31	$60	$84	$26	GR
	4				$60	$31	$60	$84	$31	SL
	5						$60	$84	$60	PB
15	1	$2	$8	$14	$61	$31	$60	$84	$2	NA
	2	$15	$20	$14	$61	$31	$60	$84	$14	GR
	3			$26	$61	$31	$60	$84	$26	GR
	4				$61	$31	$60	$84	$31	SL
	5						$60	$84	$60	PB
16	1	$2	$8	$14	$61	$31	$60	$85	$2	NA
	2	$15	$21	$14	$61	$31	$60	$85	$14	GR
	3			$27	$61	$31	$60	$85	$27	GR
	4				$61	$31	$60	$85	$31	SL
	5						$60	$85	$60	PB

Table C.1(Continued)

Analysis Period (n)	Condition State (i)	$f_n(i) = \min_a \{C_n(i,a) + \alpha \sum_{j=1}^{5} p(j \mid i,a,n) f_{n-1}(i)\}$							$f_n(i)$	a
		NA	RC	GR	CIPP	SL	PB	OR		
17	1	\$2	\$8	\$14	\$61	\$32	\$60	\$85	\$2	NA
	2	\$15	\$21	\$14	\$61	\$32	\$60	\$85	\$14	GR
	3			\$27	\$61	\$32	\$60	\$85	\$27	GR
	4				\$61	\$32	\$60	\$85	\$32	SL
	5						\$60	\$85	\$60	PB
18	1	\$2	\$8	\$14	\$61	\$32	\$60	\$85	\$2	NA
	2	\$15	\$21	\$14	\$61	\$32	\$60	\$85	\$14	GR
	3			\$27	\$61	\$32	\$60	\$85	\$27	GR
	4				\$61	\$32	\$60	\$85	\$32	SL
	5						\$60	\$85	\$60	PB
19	1	\$3	\$9	\$15	\$61	\$32	\$61	\$85	\$3	NA
	2	\$15	\$21	\$15	\$61	\$32	\$61	\$85	\$15	GR
	3			\$27	\$61	\$32	\$61	\$85	\$27	GR
	4				\$61	\$32	\$61	\$85	\$32	SL
	5						\$61	\$85	\$61	PB
20	1	\$3	\$9	\$15	\$62	\$32	\$61	\$85	\$3	NA
	2	\$16	\$22	\$15	\$62	\$32	\$61	\$85	\$15	GR
	3			\$28	\$62	\$32	\$61	\$85	\$28	GR
	4				\$62	\$32	\$61	\$85	\$32	SL
	5						\$61	\$85	\$61	PB
21	1	\$3	\$9	\$15	\$62	\$33	\$61	\$86	\$3	NA
	2	\$16	\$22	\$15	\$62	\$33	\$61	\$86	\$15	GR
	3			\$28	\$62	\$33	\$61	\$86	\$28	GR
	4				\$62	\$33	\$61	\$86	\$33	SL
	5						\$61	\$86	\$61	PB
22	1	\$4	\$10	\$15	\$62	\$33	\$62	\$86	\$4	NA
	2	\$16	\$22	\$15	\$62	\$33	\$62	\$86	\$15	GR
	3			\$28	\$62	\$33	\$62	\$86	\$28	GR
	4				\$62	\$33	\$62	\$86	\$33	SL
	5						\$62	\$86	\$62	PB
23	1	\$4	\$10	\$16	\$63	\$33	\$62	\$86	\$4	NA
	2	\$17	\$23	\$16	\$63	\$33	\$62	\$86	\$16	GR
	3			\$28	\$63	\$33	\$62	\$86	\$28	GR
	4				\$63	\$33	\$62	\$86	\$33	SL
	5						\$62	\$86	\$62	PB
24	1	\$4	\$10	\$16	\$63	\$33	\$62	\$87	\$4	NA
	2	\$17	\$23	\$16	\$63	\$33	\$62	\$87	\$16	GR
	3			\$29	\$63	\$33	\$62	\$87	\$29	GR
	4				\$63	\$33	\$62	\$87	\$33	SL
	5						\$62	\$87	\$62	PB

Table C.1(Continued)

Analysis Period (n)	Condition State (i)	$f_n(i)=\min\limits_{a}\{C_n(i,a)+\alpha\sum_{j=1}^{5}p(j\mid i,a,n)f_{n-1}(i)\}$							$f_n(i)$	a
		NA	RC	GR	CIPP	SL	PB	OR		
25	1	\$5	\$11	\$16	\$63	\$34	\$62	\$87	\$5	NA
	2	\$17	\$23	\$16	\$63	\$34	\$62	\$87	\$16	GR
	3			\$29	\$63	\$34	\$62	\$87	\$29	GR
	4				\$63	\$34	\$62	\$87	\$34	SL
	5						\$62	\$87	\$62	PB
26	1	\$5	\$11	\$17	\$64	\$34	\$63	\$87	\$5	NA
	2	\$18	\$24	\$17	\$64	\$34	\$63	\$87	\$17	GR
	3			\$30	\$64	\$34	\$63	\$87	\$30	GR
	4				\$64	\$34	\$63	\$87	\$34	SL
	5						\$63	\$87	\$63	PB
27	1	\$6	\$11	\$17	\$64	\$35	\$63	\$88	\$6	NA
	2	\$18	\$24	\$17	\$64	\$35	\$63	\$88	\$17	GR
	3			\$30	\$64	\$35	\$63	\$88	\$30	GR
	4				\$64	\$35	\$63	\$88	\$35	SL
	5						\$63	\$88	\$63	PB
28	1	\$6	\$12	\$18	\$65	\$35	\$64	\$88	\$6	NA
	2	\$19	\$25	\$18	\$65	\$35	\$64	\$88	\$18	GR
	3			\$31	\$65	\$35	\$64	\$88	\$31	GR
	4				\$65	\$35	\$64	\$88	\$35	SL
	5						\$64	\$88	\$64	PB
29	1	\$6	\$12	\$18	\$65	\$36	\$64	\$89	\$6	NA
	2	\$19	\$25	\$18	\$65	\$36	\$64	\$89	\$18	GR
	3			\$31	\$65	\$36	\$64	\$89	\$31	GR
	4				\$65	\$36	\$64	\$89	\$36	SL
	5						\$64	\$89	\$64	PB
30	1	\$7	\$13	\$19	\$66	\$36	\$65	\$89	\$7	NA
	2	\$20	\$26	\$19	\$66	\$36	\$65	\$89	\$19	GR
	3			\$31	\$66	\$36	\$65	\$89	\$31	GR
	4				\$66	\$36	\$65	\$89	\$36	SL
	5						\$65	\$89	\$65	PB
31	1	\$89	\$13	\$19	\$66	\$36	\$65	\$90	\$13	RC
	2	\$89	\$26	\$19	\$66	\$36	\$65	\$90	\$19	GR
	3			\$32	\$66	\$36	\$65	\$90	\$32	GR
	4				\$66	\$36	\$65	\$90	\$36	SL
	5						\$65	\$90	\$65	PB
32	1	\$90	\$20	\$26	\$73	\$43	\$72	\$96	\$20	RC
	2	\$90	\$27	\$26	\$73	\$43	\$72	\$96	\$26	GR
	3			\$33	\$73	\$43	\$72	\$96	\$33	GR
	4				\$73	\$43	\$72	\$96	\$43	SL
	5						\$72	\$96	\$72	PB

Table C.1(Continued)

Analysis Period (n)	Condition State (i)	$f_n(i) = \min_a \{C_n(i,a) + \alpha\sum_{j=1}^{5} p(j\mid i,a,n) f_{n-1}(i)\}$							$f_n(i)$	a
		NA	RC	GR	CIPP	SL	PB	OR		
33	1	\$96	\$26	\$32	\$79	\$49	\$78	\$102	\$26	RC
	2	\$96	\$32	\$32	\$79	\$49	\$78	\$102	\$32	GR
	3			\$38	\$79	\$49	\$78	\$102	\$38	GR
	4				\$79	\$49	\$78	\$102	\$49	SL
	5						\$78	\$102	\$78	PB
34	1	\$102	\$32	\$38	\$85	\$55	\$84	\$109	\$32	RC
	2	\$102	\$38	\$38	\$85	\$55	\$84	\$109	\$38	GR
	3			\$44	\$85	\$55	\$84	\$109	\$44	GR
	4				\$85	\$55	\$84	\$109	\$55	SL
	5						\$84	\$109	\$84	PB
35	1	\$109	\$38	\$44	\$91	\$62	\$90	\$115	\$38	RC
	2	\$109	\$45	\$44	\$91	\$62	\$90	\$115	\$44	GR
	3			\$51	\$91	\$62	\$90	\$115	\$51	GR
	4				\$91	\$62	\$90	\$115	\$62	SL
	5						\$90	\$115	\$90	PB
36	1	\$115	\$45	\$51	\$97	\$68	\$97	\$121	\$45	RC
	2	\$115	\$51	\$51	\$97	\$68	\$97	\$121	\$51	GR
	3			\$57	\$97	\$68	\$97	\$121	\$57	GR
	4				\$97	\$68	\$97	\$121	\$68	SL
	5						\$97	\$121	\$97	PB
37	1	\$121	\$51	\$57	\$104	\$74	\$103	\$127	\$51	RC
	2	\$121	\$57	\$57	\$104	\$74	\$103	\$127	\$57	GR
	3			\$63	\$104	\$74	\$103	\$127	\$63	GR
	4				\$104	\$74	\$103	\$127	\$74	SL
	5						\$103	\$127	\$103	PB
38	1	\$127	\$57	\$63	\$110	\$81	\$109	\$134	\$57	RC
	2	\$127	\$64	\$63	\$110	\$81	\$109	\$134	\$63	GR
	3			\$70	\$110	\$81	\$109	\$134	\$70	GR
	4				\$110	\$81	\$109	\$134	\$81	SL
	5						\$109	\$134	\$109	PB
39	1	\$134	\$64	\$70	\$117	\$87	\$116	\$140	\$64	RC
	2	\$134	\$70	\$70	\$117	\$87	\$116	\$140	\$70	GR
	3			\$76	\$117	\$87	\$116	\$140	\$76	GR
	4				\$117	\$87	\$116	\$140	\$87	SL
	5						\$116	\$140	\$116	PB
40	1	\$140	\$70	\$76	\$123	\$93	\$122	\$147	\$70	RC
	2	\$140	\$77	\$76	\$123	\$93	\$122	\$147	\$76	GR
	3			\$83	\$123	\$93	\$122	\$147	\$83	GR
	4				\$123	\$93	\$122	\$147	\$93	SL
	5						\$122	\$147	\$122	PB

Appendix D: Asset Values Based on Five-Year Investment Plan 1

Table D.1: Estimated asset values in year 1 (5-year investment plan 1)

Available Fund = $14,758

(1) No.	(2) FSN	(3) Length (ft)	(4) Size (in)	(5) Material	(6) Year	(7) M & R Alternative	(8) Unit Cost ($/LF)	(9) M & R Cost	(10) Base Value	(11) Rating	(12) Deteriorated Value	(13) Expected Added Value	(14) Deteriorated Value =(12)+(13)	(15) Book Value	(16) Modified Approach
1	51115	54	8	VC	1965	Pipe Bursting	$58	$3,142	$684	5	$0	$3,142	$3,142	$3,390	$3,826
2	39249	78	8	VC	1962	Pipe Bursting	$58	$4,539	$887	5	$0	$4,539	$4,539	$4,814	$5,426
3	57459	123	8	VC	1962	Pipe Bursting	$58	$0	$1,399	5	$0	$0	$0	$434	$1,399
4	57966	143	8	VC	1962	Pipe Bursting	$58	$0	$1,627	5	$0	$0	$0	$505	$1,627
5	14520	333	8	VC	1968	Pipe Bursting	$58	$0	$5,017	5	$0	$0	$0	$2,076	$5,017
6	14783	16	8	VC	1968	Sliplining	$30	$473	$241	4.14	$52	$473	$524	$573	$714
7	58572	67	8	VC	1966	Sliplining	$30	$1,980	$891	4.14	$191	$1,980	$2,171	$2,317	$2,870
8	51488	117	8	VC	1966	Sliplining	$30	$3,457	$1,555	4.14	$333	$3,457	$3,790	$4,047	$5,012
9	51938	193	8	VC	1966	Sliplining	$30	$0	$2,566	4.14	$550	$0	$550	$973	$2,566
10	51507	298	8	VC	1966	Sliplining	$30	$0	$3,961	4.14	$849	$0	$849	$1,503	$3,961
11	59279	37	8	VC	1987	Grouting	$12	$437	$2,127	3.05	$1,034	$388	$1,422	$2,014	$2,127
12	51474	118	8	VC	1965	Grouting	$12	$0	$1,495	3.05	$727	$0	$727	$541	$1,495
13	51444	174	8	VC	1968	Grouting	$12	$0	$2,622	3.05	$1,275	$0	$1,275	$1,085	$2,622
14	19105	246	8	VC	1975	Grouting	$12	$0	$7,098	3.05	$3,452	$0	$3,452	$3,794	$7,098
15	58571	342	8	VC	1966	Grouting	$12	$0	$4,546	3.05	$2,211	$0	$2,211	$1,724	$4,546
16	18434	127	8	VC	1971	No Action	$0	$0	$2,619	2.06	$1,928	$0	$1,928	$1,219	$2,619
17	852	202	8	VC	1980	No Action	$0	$0	$8,530	2.06	$6,279	$0	$6,279	$5,294	$8,530
18	58769	268	8	VC	1973	No Action	$0	$0	$6,625	2.06	$4,877	$0	$4,877	$3,313	$6,625
19	58798	295	8	VC	1973	No Action	$0	$0	$7,292	2.06	$5,368	$0	$5,368	$3,646	$7,292
20	19261	351	8	VC	1979	No Action	$0	$0	$13,750	2.06	$10,122	$0	$10,122	$8,297	$13,750
21	212	188	8	VC	1985	No Action	$0	$0	$10,288	1.02	$10,247	$0	$10,247	$7,273	$10,288
22	44827	215	8	VC	1982	No Action	$0	$0	$10,728	1.02	$10,685	$0	$10,685	$7,029	$10,728
23	51386	30	8	VC	1984	No Action	$0	$0	$1,623	1.02	$1,616	$0	$1,616	$1,119	$1,623
24	51462	170	8	VC	1980	No Action	$0	$0	$7,179	1.02	$7,150	$0	$7,150	$4,456	$7,179
25	5041025	65	8	VC	1987	No Action	$0	$0	$3,736	1.02	$3,721	$0	$3,721	$2,770	$3,736
	Total	4,250						$14,028	$109,085	3.05	$72,668		$86,646	$74,206	$122,676

Table D.2: Estimated asset values in year 2 (5-year investment plan 1)

Available Fund = $15,489

(1) No.	(2) FSN	(3) Length (ft)	(4) Size (in)	(5) Material	(6) Year	(7) M & R Alternative	(8) Unit Cost ($/LF)	(9) M & R Cost	(10) Base Value	(11) Rating	(12) Deteriorated Value	(13) Expected Added Value	(14) Deteriorated Value =(12)+(13)	(15) Book Value	(16) Modified Approach
1	51115	54	8	VC	1965	No Action	$0	$0	$684	1.02	$3,130	$0	$3,130	$3,378	$3,826
2	39249	78	8	VC	1962	No Action	$0	$0	$887	1.02	$4,521	$0	$4,521	$4,799	$5,426
3	57459	123	8	VC	1962	Pipe Bursting	$58	$7,157	$1,399	5	$0	$7,157	$7,157	$7,567	$8,557
4	57966	143	8	VC	1962	Pipe Bursting	$58	$8,321	$1,627	5	$0	$8,321	$8,321	$8,798	$9,948
5	14520	333	8	VC	1968	Pipe Bursting	$58	$0	$5,017	5	$0	$0	$0	$1,990	$5,017
6	14783	16	8	VC	1968	No Action	$0	$0	$241	1.02	$522	$0	$522	$568	$714
7	58572	67	8	VC	1966	No Action	$0	$0	$891	1.02	$2,162	$0	$2,162	$2,302	$2,870
8	51488	117	8	VC	1966	No Action	$0	$0	$1,555	1.02	$3,775	$0	$3,775	$4,020	$5,012
9	51938	193	8	VC	1966	Sliplining	$30	$0	$2,566	4.30	$450	$0	$450	$929	$2,566
10	51507	298	8	VC	1966	Sliplining	$30	$0	$3,961	4.30	$695	$0	$695	$1,434	$3,961
11	59279	37	8	VC	1987	No Action	$0	$0	$2,127	2.06	$1,402	$0	$1,402	$1,977	$2,127
12	51474	118	8	VC	1965	Grouting	$12	$0	$1,495	3.18	$679	$0	$679	$515	$1,495
13	51444	174	8	VC	1968	Grouting	$12	$0	$2,622	3.18	$1,190	$0	$1,190	$1,040	$2,622
14	19105	246	8	VC	1975	Grouting	$12	$0	$7,098	3.18	$3,223	$0	$3,223	$3,672	$7,098
15	58571	342	8	VC	1966	Grouting	$12	$0	$4,546	3.18	$2,064	$0	$2,064	$1,646	$4,546
16	18434	127	8	VC	1971	No Action	$0	$0	$2,619	2.13	$1,894	$0	$1,894	$1,174	$2,619
17	852	202	8	VC	1980	No Action	$0	$0	$8,530	2.13	$6,166	$0	$6,166	$5,147	$8,530
18	58769	268	8	VC	1973	No Action	$0	$0	$6,625	2.13	$4,789	$0	$4,789	$3,198	$6,625
19	58798	295	8	VC	1973	No Action	$0	$0	$7,292	2.13	$5,272	$0	$5,272	$3,521	$7,292
20	19261	351	8	VC	1979	No Action	$0	$0	$13,750	2.13	$9,940	$0	$9,940	$8,060	$13,750
21	212	188	8	VC	1985	No Action	$0	$0	$10,288	1.03	$10,203	$0	$10,203	$7,095	$10,288
22	44827	215	8	VC	1982	No Action	$0	$0	$10,728	1.03	$10,639	$0	$10,639	$6,844	$10,728
23	51386	30	8	VC	1984	No Action	$0	$0	$1,623	1.03	$1,609	$0	$1,609	$1,091	$1,623
24	51462	170	8	VC	1980	No Action	$0	$0	$7,179	1.03	$7,119	$0	$7,119	$4,332	$7,179
25	5041025	65	8	VC	1987	No Action	$0	$0	$3,736	1.03	$3,705	$0	$3,705	$2,705	$3,736
	Total	4,250						$15,479	$109,085	2.37	$85,149	$15,479	$100,628	$87,803	$138,154

Table D.3: Estimated asset values in year 3 (5-year investment plan 1)

Available Fund = $14,769

(1) No.	(2) FSN	(3) Length (ft)	(4) Size (in)	(5) Material	(6) Year	(7) M & R Alternative	(8) Unit Cost ($/LF)	(9) M & R Cost	(10) Base Value	(11) Rating	(12) Deteriorated Value	(13) Expected Added Value	(14) Deteriorated Value =(12)+(13)	(15) Book Value	(16) Modified Approach
1	51115	54	8	VC	1965	No Action	$0	$0	$684	1.03	$3,116	$0	$3,116	$3,366	$3,826
2	39249	78	8	VC	1962	No Action	$0	$0	$887	1.03	$4,501	$0	$4,501	$4,784	$5,426
3	57459	123	8	VC	1962	No Action	$0	$0	$1,399	1.02	$7,129	$0	$7,129	$7,543	$8,557
4	57966	143	8	VC	1962	No Action	$0	$0	$1,627	1.02	$8,288	$0	$8,288	$8,770	$9,948
5	14520	333	8	VC	1968	Pipe Bursting	$58	$0	$5,017	5	$0	$0	$0	$1,903	$5,017
6	14783	16	8	VC	1968	No Action	$0	$0	$241	1.03	$520	$0	$520	$564	$714
7	58572	67	8	VC	1966	No Action	$0	$0	$891	1.03	$2,153	$0	$2,153	$2,287	$2,870
8	51488	117	8	VC	1966	No Action	$0	$0	$1,555	1.03	$3,759	$0	$3,759	$3,993	$5,012
9	51938	193	8	VC	1966	Sliplining	$30	$5,703	$2,566	4.43	$365	$5,703	$6,067	$6,587	$8,268
10	51507	298	8	VC	1966	Sliplining	$30	$8,805	$3,961	4.43	$563	$8,805	$9,368	$10,171	$12,766
11	59279	37	8	VC	1987	No Action	$0	$0	$2,127	2.13	$1,377	$0	$1,377	$1,941	$2,127
12	51474	118	8	VC	1965	Grouting	$12	$0	$1,495	3.31	$632	$0	$632	$490	$1,495
13	51444	174	8	VC	1968	Grouting	$12	$0	$2,622	3.31	$1,108	$0	$1,108	$994	$2,622
14	19105	246	8	VC	1975	Grouting	$12	$0	$7,098	3.31	$3,001	$0	$3,001	$3,549	$7,098
15	58571	342	8	VC	1966	Grouting	$12	$0	$4,546	3.31	$1,922	$0	$1,922	$1,568	$4,546
16	18434	127	8	VC	1971	No Action	$0	$0	$2,619	2.20	$1,859	$0	$1,859	$1,129	$2,619
17	852	202	8	VC	1980	No Action	$0	$0	$8,530	2.20	$6,055	$0	$6,055	$5,000	$8,530
18	58769	268	8	VC	1973	No Action	$0	$0	$6,625	2.20	$4,703	$0	$4,703	$3,084	$6,625
19	58798	295	8	VC	1973	No Action	$0	$0	$7,292	2.20	$5,177	$0	$5,177	$3,395	$7,292
20	19261	351	8	VC	1979	No Action	$0	$0	$13,750	2.20	$9,761	$0	$9,761	$7,823	$13,750
21	212	188	8	VC	1985	No Action	$0	$0	$10,288	1.05	$10,155	$0	$10,155	$6,918	$10,288
22	44827	215	8	VC	1982	No Action	$0	$0	$10,728	1.05	$10,589	$0	$10,589	$6,659	$10,728
23	51386	30	8	VC	1984	No Action	$0	$0	$1,623	1.05	$1,602	$0	$1,602	$1,063	$1,623
24	51462	170	8	VC	1980	No Action	$0	$0	$7,179	1.05	$7,086	$0	$7,086	$4,208	$7,179
25	5041025	65	8	VC	1987	No Action	$0	$0	$3,736	1.05	$3,688	$0	$3,688	$2,641	$3,736
	Total	4,250						$14,508	$109,085	2.11	$99,108	$14,508	$113,616	$100,430	$152,662

Table D.4: Estimated asset values in year 4 (5-year investment plan 1)

Available Fund = $15,019

(1) No.	(2) FSN	(3) Length (ft)	(4) Size (in)	(5) Material	(6) Year	(7) M & R Alternative	(8) Unit Cost ($/LF)	(9) M & R Cost	(10) Base Value	(11) Rating	(12) Deteriorated Value	(13) Expected Added Value	(14) Deteriorated Value =(12)+(13)	(15) Book Value	(16) Modified Approach
1	51115	54	8	VC	1965	No Action	$0	$0	$684	1.05	$3,102	$0	$3,102	$3,355	$3,826
2	39249	78	8	VC	1962	No Action	$0	$0	$887	1.05	$4,480	$0	$4,480	$4,768	$5,426
3	57459	123	8	VC	1962	No Action	$0	$0	$1,399	1.03	$7,098	$0	$7,098	$7,519	$8,557
4	57966	143	8	VC	1962	No Action	$0	$0	$1,627	1.03	$8,252	$0	$8,252	$8,742	$9,948
5	14520	333	8	VC	1968	Pipe Bursting	$58	$0	$5,017	5	$0	$0	$0	$1,817	$5,017
6	14783	16	8	VC	1968	No Action	$0	$0	$241	1.05	$518	$0	$518	$560	$714
7	58572	67	8	VC	1966	No Action	$0	$0	$891	1.05	$2,143	$0	$2,143	$2,271	$2,870
8	51488	117	8	VC	1966	No Action	$0	$0	$1,555	1.05	$3,741	$0	$3,741	$3,966	$5,012
9	51938	193	8	VC	1966	No Action	$0	$0	$2,566	1.02	$6,043	$0	$6,043	$6,543	$8,268
10	51507	298	8	VC	1966	No Action	$0	$0	$3,961	1.02	$9,331	$0	$9,331	$10,103	$12,766
11	59279	37	8	VC	1987	No Action	$0	$0	$2,127	2.20	$1,352	$0	$1,352	$1,904	$2,127
12	51474	118	8	VC	1965	Grouting	$12	$1,395	$1,495	3.43	$587	$1,237	$1,824	$1,858	$1,495
13	51444	174	8	VC	1968	Grouting	$12	$2,056	$2,622	3.43	$1,030	$1,824	$2,854	$3,006	$2,622
14	19105	246	8	VC	1975	Grouting	$12	$2,907	$7,098	3.43	$2,788	$2,579	$5,367	$6,334	$7,098
15	58571	342	8	VC	1966	Grouting	$12	$4,042	$4,546	3.43	$1,785	$3,585	$5,371	$5,531	$4,546
16	18434	127	8	VC	1971	No Action	$0	$0	$2,619	2.27	$1,826	$0	$1,826	$1,084	$2,619
17	852	202	8	VC	1980	No Action	$0	$0	$8,530	2.27	$5,945	$0	$5,945	$4,853	$8,530
18	58769	268	8	VC	1973	No Action	$0	$0	$6,625	2.27	$4,617	$0	$4,617	$2,970	$6,625
19	58798	295	8	VC	1973	No Action	$0	$0	$7,292	2.27	$5,083	$0	$5,083	$3,269	$7,292
20	19261	351	8	VC	1979	No Action	$0	$0	$13,750	2.27	$9,583	$0	$9,583	$7,586	$13,750
21	212	188	8	VC	1985	No Action	$0	$0	$10,288	1.07	$10,105	$0	$10,105	$6,740	$10,288
22	44827	215	8	VC	1982	No Action	$0	$0	$10,728	1.07	$10,537	$0	$10,537	$6,474	$10,728
23	51386	30	8	VC	1984	No Action	$0	$0	$1,623	1.07	$1,594	$0	$1,594	$1,035	$1,623
24	51462	170	8	VC	1980	No Action	$0	$0	$7,179	1.07	$7,051	$0	$7,051	$4,084	$7,179
25	5041025	65	8	VC	1987	No Action	$0	$0	$3,736	1.07	$3,669	$0	$3,669	$2,577	$3,736
	Total	4,250						$10,401	$109,085	1.88	$112,259	$9,225	$121,485	$108,950	$152,662

Table D.5: Estimated asset values in year 5 (5-year investment plan 1)

Available Fund = $19,377

(1) No.	(2) FSN	(3) Length (ft)	(4) Size (in)	(5) Material	(6) Year	(7) M & R Alternative	(8) Unit Cost ($/LF)	(9) M & R Cost	(10) Base Value	(11) Rating	(12) Deteriorated Value	(13) Expected Added Value	(14) Deteriorated Value =(12)+(13)	(15) Book Value	(16) Modified Approach
1	51115	54	8	VC	1965	No Action	$0	$0	$684	1.07	$3,086	$0	$3,086	$3,343	$3,826
2	39249	78	8	VC	1962	No Action	$0	$0	$887	1.07	$4,458	$0	$4,458	$4,753	$5,426
3	57459	123	8	VC	1962	No Action	$0	$0	$1,399	1.05	$7,065	$0	$7,065	$7,495	$8,557
4	57966	143	8	VC	1962	No Action	$0	$0	$1,627	1.05	$8,214	$0	$8,214	$8,714	$9,948
5	14520	333	8	VC	1968	Pipe Bursting	$58	$19,377	$5,017	5	$0	$19,377	$19,377	$21,107	$24,395
6	14783	16	8	VC	1968	No Action	$0	$0	$241	1.07	$515	$0	$515	$556	$714
7	58572	67	8	VC	1966	No Action	$0	$0	$891	1.07	$2,132	$0	$2,132	$2,256	$2,870
8	51488	117	8	VC	1966	No Action	$0	$0	$1,555	1.07	$3,723	$0	$3,723	$3,940	$5,012
9	51938	193	8	VC	1966	No Action	$0	$0	$2,566	1.03	$6,017	$0	$6,017	$6,499	$8,268
10	51507	298	8	VC	1966	No Action	$0	$0	$3,961	1.03	$9,290	$0	$9,290	$10,034	$12,766
11	59279	37	8	VC	1987	No Action	$0	$0	$2,127	2.27	$1,328	$0	$1,328	$1,867	$2,127
12	51474	118	8	VC	1965	No Action	$0	$0	$1,495	2.06	$1,799	$0	$1,799	$1,833	$1,495
13	51444	174	8	VC	1968	No Action	$0	$0	$2,622	2.06	$2,814	$0	$2,814	$2,960	$2,622
14	19105	246	8	VC	1975	No Action	$0	$0	$7,098	2.06	$5,292	$0	$5,292	$6,212	$7,098
15	58571	342	8	VC	1966	No Action	$0	$0	$4,546	2.06	$5,296	$0	$5,296	$5,453	$4,546
16	18434	127	8	VC	1971	No Action	$0	$0	$2,619	2.35	$1,792	$0	$1,792	$1,039	$2,619
17	852	202	8	VC	1980	No Action	$0	$0	$8,530	2.35	$5,837	$0	$5,837	$4,706	$8,530
18	58769	268	8	VC	1973	No Action	$0	$0	$6,625	2.35	$4,533	$0	$4,533	$2,856	$6,625
19	58798	295	8	VC	1973	No Action	$0	$0	$7,292	2.35	$4,990	$0	$4,990	$3,143	$7,292
20	19261	351	8	VC	1979	No Action	$0	$0	$13,750	2.35	$9,409	$0	$9,409	$7,349	$13,750
21	212	188	8	VC	1985	No Action	$0	$0	$10,288	1.09	$10,052	$0	$10,052	$6,563	$10,288
22	44827	215	8	VC	1982	No Action	$0	$0	$10,728	1.09	$10,482	$0	$10,482	$6,289	$10,728
23	51386	30	8	VC	1984	No Action	$0	$0	$1,623	1.09	$1,585	$0	$1,585	$1,007	$1,623
24	51462	170	8	VC	1980	No Action	$0	$0	$7,179	1.09	$7,014	$0	$7,014	$3,961	$7,179
25	5041025	65	8	VC	1987	No Action	$0	$0	$3,736	1.09	$3,650	$0	$3,650	$2,512	$3,736
	Total	4,250						$19,377	$109,085	1.69	$120,375	$19,377	$139,752	$126,446	$172,039

Appendix E: Asset Values Based on Five-Year Investment Plan 2

Table E.1: Estimated asset values in year 1 (5-year investment plan 2)

Available Fund = $26,565

(1) No.	(2) FSN	(3) Length (ft)	(4) Size (in)	(5) Material	(6) Year	(7) M & R Alternative	(8) Unit Cost ($/LF)	(9) M & R Cost	(10) Base Value	(11) Rating	(12) Deteriorated Value	(13) Expected Added Value	(14) Deteriorated Value =(12)+(13)	(15) Book Value	(16) Modified Approach
1	51115	54	8	VC	1965	Pipe Bursting	$58	$3,142	$684	5	$0	$3,142	$3,142	$3,390	$3,826
2	39249	78	8	VC	1962	Pipe Bursting	$58	$4,539	$887	5	$0	$4,539	$4,539	$4,814	$5,426
3	57459	123	8	VC	1962	Pipe Bursting	$58	$7,157	$1,399	5	$0	$7,157	$7,157	$7,592	$8,557
4	57966	143	8	VC	1962	Pipe Bursting	$58	$8,321	$1,627	5	$0	$8,321	$8,321	$8,826	$9,948
5	14520	333	8	VC	1968	Pipe Bursting	$58	$0	$5,017	5	$0	$0	$0	$2,076	$5,017
6	14783	16	8	VC	1968	Sliplining	$30	$473	$241	4.14	$52	$473	$524	$573	$714
7	58572	67	8	VC	1966	Sliplining	$30	$1,980	$891	4.14	$191	$1,980	$2,171	$2,317	$2,870
8	51488	117	8	VC	1966	Sliplining	$30	$0	$1,555	4.14	$333	$0	$333	$590	$1,555
9	51938	193	8	VC	1966	Sliplining	$30	$0	$2,566	4.14	$550	$0	$550	$973	$2,566
10	51507	298	8	VC	1966	Sliplining	$30	$0	$3,961	4.14	$849	$0	$849	$1,503	$3,961
11	59279	37	8	VC	1987	Grouting	$12	$0	$2,127	3.05	$1,034	$0	$1,034	$1,577	$2,127
12	51474	118	8	VC	1965	Grouting	$12	$0	$1,495	3.05	$727	$0	$727	$541	$1,495
13	51444	174	8	VC	1968	Grouting	$12	$0	$2,622	3.05	$1,275	$0	$1,275	$1,085	$2,622
14	19105	246	8	VC	1975	Grouting	$12	$0	$7,098	3.05	$3,452	$0	$3,452	$3,794	$7,098
15	58571	342	8	VC	1966	Grouting	$12	$0	$4,546	3.05	$2,211	$0	$2,211	$1,724	$4,546
16	18434	127	8	VC	1971	No Action	$0	$0	$2,619	2.06	$1,928	$0	$1,928	$1,219	$2,619
17	852	202	8	VC	1980	No Action	$0	$0	$8,530	2.06	$6,279	$0	$6,279	$5,294	$8,530
18	58769	268	8	VC	1973	No Action	$0	$0	$6,625	2.06	$4,877	$0	$4,877	$3,313	$6,625
19	58798	295	8	VC	1973	No Action	$0	$0	$7,292	2.06	$5,368	$0	$5,368	$3,646	$7,292
20	19261	351	8	VC	1979	No Action	$0	$0	$13,750	2.06	$10,122	$0	$10,122	$8,297	$13,750
21	212	188	8	VC	1985	No Action	$0	$0	$10,288	1.02	$10,247	$0	$10,247	$7,273	$10,288
22	44827	215	8	VC	1982	No Action	$0	$0	$10,728	1.02	$10,685	$0	$10,685	$7,029	$10,728
23	51386	30	8	VC	1984	No Action	$0	$0	$1,623	1.02	$1,616	$0	$1,616	$1,119	$1,623
24	51462	170	8	VC	1980	No Action	$0	$0	$7,179	1.02	$7,150	$0	$7,150	$4,456	$7,179
25	5041025	65	8	VC	1987	No Action	$0	$0	$3,736	1.02	$3,721	$0	$3,721	$2,770	$3,736
	Total	4,250						$25,612	$109,085	3.05	$72,668		$98,280	$85,790	$134,697

Table E.2: Estimated asset values in year 2 (5-year investment plan 2)

Available Fund = $21,615

(1) No.	(2) FSN	(3) Length (ft)	(4) Size (in)	(5) Material	(6) Year	(7) M & R Alternative	(8) Unit Cost ($/LF)	(9) M & R Cost	(10) Base Value	(11) Rating	(12) Deteriorated Value	(13) Expected Added Value	(14) Deteriorated Value =(12)+(13)	(15) Book Value	(16) Modified Approach
1	51115	54	8	VC	1965	No Action	$0	$0	$684	1.02	$3,130	$0	$3,130	$3,378	$3,826
2	39249	78	8	VC	1962	No Action	$0	$0	$887	1.02	$4,521	$0	$4,521	$4,799	$5,426
3	57459	123	8	VC	1962	No Action	$0	$0	$1,399	1.02	$7,129	$0	$7,129	$7,567	$8,557
4	57966	143	8	VC	1962	No Action	$0	$0	$1,627	1.02	$8,288	$0	$8,288	$8,798	$9,948
5	14520	333	8	VC	1968	Pipe Bursting	$58	$0	$5,017	5	$0	$0	$0	$1,990	$5,017
6	14783	16	8	VC	1968	No Action	$0	$0	$241	1.02	$522	$0	$522	$568	$714
7	58572	67	8	VC	1966	No Action	$0	$0	$891	1.02	$2,162	$0	$2,162	$2,302	$2,870
8	51488	117	8	VC	1966	Sliplining	$30	$3,457	$1,555	4.30	$273	$3,457	$3,730	$4,020	$5,012
9	51938	193	8	VC	1966	Sliplining	$30	$5,703	$2,566	4.30	$450	$5,703	$6,153	$6,631	$8,268
10	51507	298	8	VC	1966	Sliplining	$30	$8,805	$3,961	4.30	$695	$8,805	$9,500	$10,239	$12,766
11	59279	37	8	VC	1987	Grouting	$12	$437	$2,127	3.18	$965	$388	$1,353	$1,977	$2,127
12	51474	118	8	VC	1965	Grouting	$12	$1,395	$1,495	3.18	$679	$1,237	$1,916	$1,910	$1,495
13	51444	174	8	VC	1968	Grouting	$12	$0	$2,622	3.18	$1,190	$0	$1,190	$1,040	$2,622
14	19105	246	8	VC	1975	Grouting	$12	$0	$7,098	3.18	$3,223	$0	$3,223	$3,672	$7,098
15	58571	342	8	VC	1966	Grouting	$12	$0	$4,546	3.18	$2,064	$0	$2,064	$1,646	$4,546
16	18434	127	8	VC	1971	No Action	$0	$0	$2,619	2.13	$1,894	$0	$1,894	$1,174	$2,619
17	852	202	8	VC	1980	No Action	$0	$0	$8,530	2.13	$6,166	$0	$6,166	$5,147	$8,530
18	58769	268	8	VC	1973	No Action	$0	$0	$6,625	2.13	$4,789	$0	$4,789	$3,198	$6,625
19	58798	295	8	VC	1973	No Action	$0	$0	$7,292	2.13	$5,272	$0	$5,272	$3,521	$7,292
20	19261	351	8	VC	1979	No Action	$0	$0	$13,750	2.13	$9,940	$0	$9,940	$8,060	$13,750
21	212	188	8	VC	1985	No Action	$0	$0	$10,288	1.03	$10,203	$0	$10,203	$7,095	$10,288
22	44827	215	8	VC	1982	No Action	$0	$0	$10,728	1.03	$10,639	$0	$10,639	$6,844	$10,728
23	51386	30	8	VC	1984	No Action	$0	$0	$1,623	1.03	$1,609	$0	$1,609	$1,091	$1,623
24	51462	170	8	VC	1980	No Action	$0	$0	$7,179	1.03	$7,119	$0	$7,119	$4,332	$7,179
25	5041025	65	8	VC	1987	No Action	$0	$0	$3,736	1.03	$3,705	$0	$3,705	$2,705	$3,736
	Total	4,250						$19,796	$109,085	2.23	$96,627		$116,217	$103,705	$152,662

Table E.3: Estimated asset values in year 3 (5-year investment plan 2)

Available Fund = $16,577

(1) No.	(2) FSN	(3) Length (ft)	(4) Size (in)	(5) Material	(6) Year	(7) M & R Alternative	(8) Unit Cost ($/LF)	(9) M & R Cost	(10) Base Value	(11) Rating	(12) Deteriorated Value	(13) Expected Added Value	(14) Deteriorated Value =(12)+(13)	(15) Book Value	(16) Modified Approach
1	51115	54	8	VC	1965	No Action	$0	$0	$684	1.03	$3,116	$0	$3,116	$3,366	$3,826
2	39249	78	8	VC	1962	No Action	$0	$0	$887	1.03	$4,501	$0	$4,501	$4,784	$5,426
3	57459	123	8	VC	1962	No Action	$0	$0	$1,399	1.03	$7,098	$0	$7,098	$7,543	$8,557
4	57966	143	8	VC	1962	No Action	$0	$0	$1,627	1.03	$8,252	$0	$8,252	$8,770	$9,948
5	14520	333	8	VC	1968	Pipe Bursting	$58	$0	$5,017	5	$0	$0	$0	$1,903	$5,017
6	14783	16	8	VC	1968	No Action	$0	$0	$241	1.03	$520	$0	$520	$564	$714
7	58572	67	8	VC	1966	No Action	$0	$0	$891	1.03	$2,153	$0	$2,153	$2,287	$2,870
8	51488	117	8	VC	1966	No Action	$0	$0	$1,555	1.02	$3,715	$0	$3,715	$3,993	$5,012
9	51938	193	8	VC	1966	No Action	$0	$0	$2,566	1.02	$6,128	$0	$6,128	$6,587	$8,268
10	51507	298	8	VC	1966	No Action	$0	$0	$3,961	1.02	$9,462	$0	$9,462	$10,171	$12,766
11	59279	37	8	VC	1987	No Action	$0	$0	$2,127	2.06	$1,335	$0	$1,335	$1,941	$2,127
12	51474	118	8	VC	1965	No Action	$0	$0	$1,495	2.06	$1,889	$0	$1,889	$1,884	$1,495
13	51444	174	8	VC	1968	Grouting	$12	$2,056	$2,622	3.18	$1,190	$1,824	$3,014	$3,051	$2,622
14	19105	246	8	VC	1975	Grouting	$12	$2,907	$7,098	3.18	$3,223	$2,579	$5,801	$6,457	$7,098
15	58571	342	8	VC	1966	Grouting	$12	$4,042	$4,546	3.18	$2,064	$3,585	$5,649	$5,610	$4,546
16	18434	127	8	VC	1971	No Action	$0	$0	$2,619	2.20	$1,859	$0	$1,859	$1,129	$2,619
17	852	202	8	VC	1980	No Action	$0	$0	$8,530	2.20	$6,055	$0	$6,055	$5,000	$8,530
18	58769	268	8	VC	1973	No Action	$0	$0	$6,625	2.20	$4,703	$0	$4,703	$3,084	$6,625
19	58798	295	8	VC	1973	No Action	$0	$0	$7,292	2.20	$5,177	$0	$5,177	$3,395	$7,292
20	19261	351	8	VC	1979	No Action	$0	$0	$13,750	2.20	$9,761	$0	$9,761	$7,823	$13,750
21	212	188	8	VC	1985	No Action	$0	$0	$10,288	1.05	$10,155	$0	$10,155	$6,918	$10,288
22	44827	215	8	VC	1982	No Action	$0	$0	$10,728	1.05	$10,589	$0	$10,589	$6,659	$10,728
23	51386	30	8	VC	1984	No Action	$0	$0	$1,623	1.05	$1,602	$0	$1,602	$1,063	$1,623
24	51462	170	8	VC	1980	No Action	$0	$0	$7,179	1.05	$7,086	$0	$7,086	$4,208	$7,179
25	5041025	65	8	VC	1987	No Action	$0	$0	$3,736	1.05	$3,688	$0	$3,688	$2,641	$3,736
	Total	4,250						$9,006	$109,085	1.77	$115,320		$123,309	$110,831	$152,662

Table E.4: Estimated asset values in year 4 (5-year investment plan 2)

Available Fund = $16,426

(1) No.	(2) FSN	(3) Length (ft)	(4) Size (in)	(5) Material	(6) Year	(7) M & R Alternative	(8) Unit Cost ($/LF)	(9) M & R Cost	(10) Base Value	(11) Rating	(12) Deteriorated Value	(13) Expected Added Value	(14) Deteriorated Value =(12)+(13)	(15) Book Value	(16) Modified Approach
1	51115	54	8	VC	1965	No Action	$0	$0	$684	1.05	$3,102	$0	$3,102	$3,355	$3,826
2	39249	78	8	VC	1962	No Action	$0	$0	$887	1.05	$4,480	$0	$4,480	$4,768	$5,426
3	57459	123	8	VC	1962	No Action	$0	$0	$1,399	1.05	$7,065	$0	$7,065	$7,519	$8,557
4	57966	143	8	VC	1962	No Action	$0	$0	$1,627	1.05	$8,214	$0	$8,214	$8,742	$9,948
5	14520	333	8	VC	1968	Pipe Bursting	$58	$0	$5,017	5	$0	$0	$0	$1,817	$5,017
6	14783	16	8	VC	1968	No Action	$0	$0	$241	1.05	$518	$0	$518	$560	$714
7	58572	67	8	VC	1966	No Action	$0	$0	$891	1.05	$2,143	$0	$2,143	$2,271	$2,870
8	51488	117	8	VC	1966	No Action	$0	$0	$1,555	1.03	$3,699	$0	$3,699	$3,966	$5,012
9	51938	193	8	VC	1966	No Action	$0	$0	$2,566	1.03	$6,102	$0	$6,102	$6,543	$8,268
10	51507	298	8	VC	1966	No Action	$0	$0	$3,961	1.03	$9,421	$0	$9,421	$10,103	$12,766
11	59279	37	8	VC	1987	No Action	$0	$0	$2,127	2.13	$1,311	$0	$1,311	$1,904	$2,127
12	51474	118	8	VC	1965	No Action	$0	$0	$1,495	2.13	$1,855	$0	$1,855	$1,858	$1,495
13	51444	174	8	VC	1968	No Action	$0	$0	$2,622	2.06	$2,972	$0	$2,972	$3,006	$2,622
14	19105	246	8	VC	1975	No Action	$0	$0	$7,098	2.06	$5,721	$0	$5,721	$6,334	$7,098
15	58571	342	8	VC	1966	No Action	$0	$0	$4,546	2.06	$5,571	$0	$5,571	$5,531	$4,546
16	18434	127	8	VC	1971	No Action	$0	$0	$2,619	2.27	$1,826	$0	$1,826	$1,084	$2,619
17	852	202	8	VC	1980	No Action	$0	$0	$8,530	2.27	$5,945	$0	$5,945	$4,853	$8,530
18	58769	268	8	VC	1973	No Action	$0	$0	$6,625	2.27	$4,617	$0	$4,617	$2,970	$6,625
19	58798	295	8	VC	1973	No Action	$0	$0	$7,292	2.27	$5,083	$0	$5,083	$3,269	$7,292
20	19261	351	8	VC	1979	No Action	$0	$0	$13,750	2.27	$9,583	$0	$9,583	$7,586	$13,750
21	212	188	8	VC	1985	No Action	$0	$0	$10,288	1.07	$10,105	$0	$10,105	$6,740	$10,288
22	44827	215	8	VC	1982	No Action	$0	$0	$10,728	1.07	$10,537	$0	$10,537	$6,474	$10,728
23	51386	30	8	VC	1984	No Action	$0	$0	$1,623	1.07	$1,594	$0	$1,594	$1,035	$1,623
24	51462	170	8	VC	1980	No Action	$0	$0	$7,179	1.07	$7,051	$0	$7,051	$4,084	$7,179
25	5041025	65	8	VC	1987	No Action	$0	$0	$3,736	1.07	$3,669	$0	$3,669	$2,577	$3,736
	Total	4,250						$0	$109,085	1.66	$122,182		$122,182	$108,950	$152,662

Table E.5: Estimated asset values in year 5 (5-year investment plan 2)

Available Fund = $19,377

(1) No.	(2) FSN	(3) Length (ft)	(4) Size (in)	(5) Material	(6) Year	(7) M & R Alternative	(8) Unit Cost ($/LF)	(9) M & R Cost	(10) Base Value	(11) Rating	(12) Deteriorated Value	(13) Expected Added Value	(14) Deteriorated Value =(12)+(13)	(15) Book Value	(16) Modified Approach
1	51115	54	8	VC	1965	No Action	$0	$0	$684	1.07	$3,086	$0	$3,086	$3,343	$3,826
2	39249	78	8	VC	1962	No Action	$0	$0	$887	1.07	$4,458	$0	$4,458	$4,753	$5,426
3	57459	123	8	VC	1962	No Action	$0	$0	$1,399	1.07	$7,030	$0	$7,030	$7,495	$8,557
4	57966	143	8	VC	1962	No Action	$0	$0	$1,627	1.07	$8,173	$0	$8,173	$8,714	$9,948
5	14520	333	8	VC	1968	Pipe Bursting	$58	$19,377	$5,017	5	$0	$19,377	$19,377	$21,107	$24,395
6	14783	16	8	VC	1968	No Action	$0	$0	$241	1.07	$515	$0	$515	$556	$714
7	58572	67	8	VC	1966	No Action	$0	$0	$891	1.07	$2,132	$0	$2,132	$2,256	$2,870
8	51488	117	8	VC	1966	No Action	$0	$0	$1,555	1.05	$3,682	$0	$3,682	$3,940	$5,012
9	51938	193	8	VC	1966	No Action	$0	$0	$2,566	1.05	$6,073	$0	$6,073	$6,499	$8,268
10	51507	298	8	VC	1966	No Action	$0	$0	$3,961	1.05	$9,377	$0	$9,377	$10,034	$12,766
11	59279	37	8	VC	1987	No Action	$0	$0	$2,127	2.20	$1,287	$0	$1,287	$1,867	$2,127
12	51474	118	8	VC	1965	No Action	$0	$0	$1,495	2.20	$1,822	$0	$1,822	$1,833	$1,495
13	51444	174	8	VC	1968	No Action	$0	$0	$2,622	2.13	$2,919	$0	$2,919	$2,960	$2,622
14	19105	246	8	VC	1975	No Action	$0	$0	$7,098	2.13	$5,618	$0	$5,618	$6,212	$7,098
15	58571	342	8	VC	1966	No Action	$0	$0	$4,546	2.13	$5,471	$0	$5,471	$5,453	$4,546
16	18434	127	8	VC	1971	No Action	$0	$0	$2,619	2.35	$1,792	$0	$1,792	$1,039	$2,619
17	852	202	8	VC	1980	No Action	$0	$0	$8,530	2.35	$5,837	$0	$5,837	$4,706	$8,530
18	58769	268	8	VC	1973	No Action	$0	$0	$6,625	2.35	$4,533	$0	$4,533	$2,856	$6,625
19	58798	295	8	VC	1973	No Action	$0	$0	$7,292	2.35	$4,990	$0	$4,990	$3,143	$7,292
20	19261	351	8	VC	1979	No Action	$0	$0	$13,750	2.35	$9,409	$0	$9,409	$7,349	$13,750
21	212	188	8	VC	1985	No Action	$0	$0	$10,288	1.09	$10,052	$0	$10,052	$6,563	$10,288
22	44827	215	8	VC	1982	No Action	$0	$0	$10,728	1.09	$10,482	$0	$10,482	$6,289	$10,728
23	51386	30	8	VC	1984	No Action	$0	$0	$1,623	1.09	$1,585	$0	$1,585	$1,007	$1,623
24	51462	170	8	VC	1980	No Action	$0	$0	$7,179	1.09	$7,014	$0	$7,014	$3,961	$7,179
25	5041025	65	8	VC	1987	No Action	$0	$0	$3,736	1.09	$3,650	$0	$3,650	$2,512	$3,736
	Total	4,250						$19,377	$109,085	1.70	$120,988		$140,366	$126,446	$172,039

Appendix F: Asset Values Based on Five-Year Investment Plan 3

Table F.1: Estimated asset values in year 1 (5-year investment plan 3)

Available Fund = $2,952

(1) No.	(2) FSN	(3) Length (ft)	(4) Size (in)	(5) Material	(6) Year	(7) M & R Alternative	(8) Unit Cost ($/LF)	(9) M & R Cost	(10) Base Value	(11) Rating	(12) Deteriorated Value	(13) Expected Added Value	(14) Deteriorated Value =(12)+(13)	(15) Book Value	(16) Modified Approach
1	51115	54	8	VC	1965	Pipe Bursting	$58	$0	$684	5	$0	$0	$0	$248	$684
2	39249	78	8	VC	1962	Pipe Bursting	$58	$0	$887	5	$0	$0	$0	$275	$887
3	57459	123	8	VC	1962	Pipe Bursting	$58	$0	$1,399	5	$0	$0	$0	$434	$1,399
4	57966	143	8	VC	1962	Pipe Bursting	$58	$0	$1,627	5	$0	$0	$0	$505	$1,627
5	14520	333	8	VC	1968	Pipe Bursting	$58	$0	$5,017	5	$0	$0	$0	$2,076	$5,017
6	14783	16	8	VC	1968	Sliplining	$30	$473	$241	4.14	$52	$473	$524	$573	$714
7	58572	67	8	VC	1966	Sliplining	$30	$1,980	$891	4.14	$191	$1,980	$2,171	$2,317	$2,870
8	51488	117	8	VC	1966	Sliplining	$30	$0	$1,555	4.14	$333	$0	$333	$590	$1,555
9	51938	193	8	VC	1966	Sliplining	$30	$0	$2,566	4.14	$550	$0	$550	$973	$2,566
10	51507	298	8	VC	1966	Sliplining	$30	$0	$3,961	4.14	$849	$0	$849	$1,503	$3,961
11	59279	37	8	VC	1987	Grouting	$12	$437	$2,127	3.05	$1,034	$388	$1,422	$2,014	$2,127
12	51474	118	8	VC	1965	Grouting	$12	$0	$1,495	3.05	$727	$0	$727	$541	$1,495
13	51444	174	8	VC	1968	Grouting	$12	$0	$2,622	3.05	$1,275	$0	$1,275	$1,085	$2,622
14	19105	246	8	VC	1975	Grouting	$12	$0	$7,098	3.05	$3,452	$0	$3,452	$3,794	$7,098
15	58571	342	8	VC	1966	Grouting	$12	$0	$4,546	3.05	$2,211	$0	$2,211	$1,724	$4,546
16	18434	127	8	VC	1971	No Action	$0	$0	$2,619	2.06	$1,928	$0	$1,928	$1,219	$2,619
17	852	202	8	VC	1980	No Action	$0	$0	$8,530	2.06	$6,279	$0	$6,279	$5,294	$8,530
18	58769	268	8	VC	1973	No Action	$0	$0	$6,625	2.06	$4,877	$0	$4,877	$3,313	$6,625
19	58798	295	8	VC	1973	No Action	$0	$0	$7,292	2.06	$5,368	$0	$5,368	$3,646	$7,292
20	19261	351	8	VC	1979	No Action	$0	$0	$13,750	2.06	$10,122	$0	$10,122	$8,297	$13,750
21	212	188	8	VC	1985	No Action	$0	$0	$10,288	1.02	$10,247	$0	$10,247	$7,273	$10,288
22	44827	215	8	VC	1982	No Action	$0	$0	$10,728	1.02	$10,685	$0	$10,685	$7,029	$10,728
23	51386	30	8	VC	1984	No Action	$0	$0	$1,623	1.02	$1,616	$0	$1,616	$1,119	$1,623
24	51462	170	8	VC	1980	No Action	$0	$0	$7,179	1.02	$7,150	$0	$7,150	$4,456	$7,179
25	5041025	65	8	VC	1987	No Action	$0	$0	$3,736	1.02	$3,721	$0	$3,721	$2,770	$3,736
	Total	4,250						$2,890	$109,085	3.05	$72,668		$75,508	$63,068	$111,538

Table F.2: Estimated asset values in year 2 (5-year investment plan 3)

Available Fund = $8,917

(1) No.	(2) FSN	(3) Length (ft)	(4) Size (in)	(5) Material	(6) Year	(7) M & R Alternative	(8) Unit Cost ($/LF)	(9) M & R Cost	(10) Base Value	(11) Rating	(12) Deteriorated Value	(13) Expected Added Value	(14) Deteriorated Value =(12)+(13)	(15) Book Value	(16) Modified Approach
1	51115	54	8	VC	1965	Pipe Bursting	$58	$3,142	$684	5	$0	$3,142	$3,142	$3,378	$3,826
2	39249	78	8	VC	1962	Pipe Bursting	$58	$4,539	$887	5	$0	$4,539	$4,539	$4,799	$5,426
3	57459	123	8	VC	1962	Pipe Bursting	$58	$0	$1,399	5	$0	$0	$0	$410	$1,399
4	57966	143	8	VC	1962	Pipe Bursting	$58	$0	$1,627	5	$0	$0	$0	$477	$1,627
5	14520	333	8	VC	1968	Pipe Bursting	$58	$0	$5,017	5	$0	$0	$0	$1,990	$5,017
6	14783	16	8	VC	1968	No Action	$0	$0	$241	1.02	$522	$0	$522	$568	$714
7	58572	67	8	VC	1966	No Action	$0	$0	$891	1.02	$2,162	$0	$2,162	$2,302	$2,870
8	51488	117	8	VC	1966	Sliplining	$30	$0	$1,555	4.30	$273	$0	$273	$563	$1,555
9	51938	193	8	VC	1966	Sliplining	$30	$0	$2,566	4.30	$450	$0	$450	$929	$2,566
10	51507	298	8	VC	1966	Sliplining	$30	$0	$3,961	4.30	$695	$0	$695	$1,434	$3,961
11	59279	37	8	VC	1987	No Action	$0	$0	$2,127	2.06	$1,402	$0	$1,402	$1,977	$2,127
12	51474	118	8	VC	1965	Grouting	$12	$0	$1,495	3.18	$679	$0	$679	$515	$1,495
13	51444	174	8	VC	1968	Grouting	$12	$0	$2,622	3.18	$1,190	$0	$1,190	$1,040	$2,622
14	19105	246	8	VC	1975	Grouting	$12	$0	$7,098	3.18	$3,223	$0	$3,223	$3,672	$7,098
15	58571	342	8	VC	1966	Grouting	$12	$0	$4,546	3.18	$2,064	$0	$2,064	$1,646	$4,546
16	18434	127	8	VC	1971	No Action	$0	$0	$2,619	2.13	$1,894	$0	$1,894	$1,174	$2,619
17	852	202	8	VC	1980	No Action	$0	$0	$8,530	2.13	$6,166	$0	$6,166	$5,147	$8,530
18	58769	268	8	VC	1973	No Action	$0	$0	$6,625	2.13	$4,789	$0	$4,789	$3,198	$6,625
19	58798	295	8	VC	1973	No Action	$0	$0	$7,292	2.13	$5,272	$0	$5,272	$3,521	$7,292
20	19261	351	8	VC	1979	No Action	$0	$0	$13,750	2.13	$9,940	$0	$9,940	$8,060	$13,750
21	212	188	8	VC	1985	No Action	$0	$0	$10,288	1.03	$10,203	$0	$10,203	$7,095	$10,288
22	44827	215	8	VC	1982	No Action	$0	$0	$10,728	1.03	$10,639	$0	$10,639	$6,844	$10,728
23	51386	30	8	VC	1984	No Action	$0	$0	$1,623	1.03	$1,609	$0	$1,609	$1,091	$1,623
24	51462	170	8	VC	1980	No Action	$0	$0	$7,179	1.03	$7,119	$0	$7,119	$4,332	$7,179
25	5041025	65	8	VC	1987	No Action	$0	$0	$3,736	1.03	$3,705	$0	$3,705	$2,705	$3,736
	Total	4,250						$7,681	$109,085	2.82	$73,996		$81,677	$68,868	$119,219

Table F.3: Estimated asset values in year 3 (5-year investment plan 3)

Available Fund = $15,994

(1) No.	(2) FSN	(3) Length (ft)	(4) Size (in)	(5) Material	(6) Year	(7) M & R Alternative	(8) Unit Cost ($/LF)	(9) M & R Cost	(10) Base Value	(11) Rating	(12) Deteriorated Value	(13) Expected Added Value	(14) Deteriorated Value =(12)+(13)	(15) Book Value	(16) Modified Approach
1	51115	54	8	VC	1965	No Action	$0	$0	$684	1.02	$3,130	$0	$3,130	$3,366	$3,826
2	39249	78	8	VC	1962	No Action	$0	$0	$887	1.02	$4,521	$0	$4,521	$4,784	$5,426
3	57459	123	8	VC	1962	Pipe Bursting	$58	$7,157	$1,399	5	$0	$7,157	$7,157	$7,543	$8,557
4	57966	143	8	VC	1962	Pipe Bursting	$58	$8,321	$1,627	5	$0	$8,321	$8,321	$8,770	$9,948
5	14520	333	8	VC	1968	Pipe Bursting	$58	$0	$5,017	5	$0	$0	$0	$1,903	$5,017
6	14783	16	8	VC	1968	No Action	$0	$0	$241	1.03	$520	$0	$520	$564	$714
7	58572	67	8	VC	1966	No Action	$0	$0	$891	1.03	$2,153	$0	$2,153	$2,287	$2,870
8	51488	117	8	VC	1966	Sliplining	$30	$0	$1,555	4.43	$221	$0	$221	$536	$1,555
9	51938	193	8	VC	1966	Sliplining	$30	$0	$2,566	4.43	$365	$0	$365	$885	$2,566
10	51507	298	8	VC	1966	Sliplining	$30	$0	$3,961	4.43	$563	$0	$563	$1,366	$3,961
11	59279	37	8	VC	1987	No Action	$0	$0	$2,127	2.13	$1,377	$0	$1,377	$1,941	$2,127
12	51474	118	8	VC	1965	Grouting	$12	$0	$1,495	3.31	$632	$0	$632	$490	$1,495
13	51444	174	8	VC	1968	Grouting	$12	$0	$2,622	3.31	$1,108	$0	$1,108	$994	$2,622
14	19105	246	8	VC	1975	Grouting	$12	$0	$7,098	3.31	$3,001	$0	$3,001	$3,549	$7,098
15	58571	342	8	VC	1966	Grouting	$12	$0	$4,546	3.31	$1,922	$0	$1,922	$1,568	$4,546
16	18434	127	8	VC	1971	No Action	$0	$0	$2,619	2.20	$1,859	$0	$1,859	$1,129	$2,619
17	852	202	8	VC	1980	No Action	$0	$0	$8,530	2.20	$6,055	$0	$6,055	$5,000	$8,530
18	58769	268	8	VC	1973	No Action	$0	$0	$6,625	2.20	$4,703	$0	$4,703	$3,084	$6,625
19	58798	295	8	VC	1973	No Action	$0	$0	$7,292	2.20	$5,177	$0	$5,177	$3,395	$7,292
20	19261	351	8	VC	1979	No Action	$0	$0	$13,750	2.20	$9,761	$0	$9,761	$7,823	$13,750
21	212	188	8	VC	1985	No Action	$0	$0	$10,288	1.05	$10,155	$0	$10,155	$6,918	$10,288
22	44827	215	8	VC	1982	No Action	$0	$0	$10,728	1.05	$10,589	$0	$10,589	$6,659	$10,728
23	51386	30	8	VC	1984	No Action	$0	$0	$1,623	1.05	$1,602	$0	$1,602	$1,063	$1,623
24	51462	170	8	VC	1980	No Action	$0	$0	$7,179	1.05	$7,086	$0	$7,086	$4,208	$7,179
25	5041025	65	8	VC	1987	No Action	$0	$0	$3,736	1.05	$3,688	$0	$3,688	$2,641	$3,736
	Total	4,250						$15,479	$109,085	2.56	$80,186		$95,665	$82,466	$134,697

Table F.4: Estimated asset values in year 4 (5-year investment plan 3)

Available Fund = $21,177

(1) No.	(2) FSN	(3) Length (ft)	(4) Size (in)	(5) Material	(6) Year	(7) M & R Alternative	(8) Unit Cost ($/LF)	(9) M & R Cost	(10) Base Value	(11) Rating	(12) Deteriorated Value	(13) Expected Added Value	(14) Deteriorated Value =(12)+(13)	(15) Book Value	(16) Modified Approach
1	51115	54	8	VC	1965	No Action	$0	$0	$684	1.03	$3,116	$0	$3,116	$3,355	$3,826
2	39249	78	8	VC	1962	No Action	$0	$0	$887	1.03	$4,501	$0	$4,501	$4,768	$5,426
3	57459	123	8	VC	1962	No Action	$0	$0	$1,399	1.02	$7,129	$0	$7,129	$7,519	$8,557
4	57966	143	8	VC	1962	No Action	$0	$0	$1,627	1.02	$8,288	$0	$8,288	$8,742	$9,948
5	14520	333	8	VC	1968	Pipe Bursting	$58	$19,377	$5,017	5	$0	$19,377	$19,377	$21,194	$24,395
6	14783	16	8	VC	1968	No Action	$0	$0	$241	1.05	$518	$0	$518	$560	$714
7	58572	67	8	VC	1966	No Action	$0	$0	$891	1.05	$2,143	$0	$2,143	$2,271	$2,870
8	51488	117	8	VC	1966	Sliplining	$30	$0	$1,555	4.54	$177	$0	$177	$509	$1,555
9	51938	193	8	VC	1966	Sliplining	$30	$0	$2,566	4.54	$293	$0	$293	$840	$2,566
10	51507	298	8	VC	1966	Sliplining	$30	$0	$3,961	4.54	$452	$0	$452	$1,298	$3,961
11	59279	37	8	VC	1987	No Action	$0	$0	$2,127	2.20	$1,352	$0	$1,352	$1,904	$2,127
12	51474	118	8	VC	1965	Grouting	$12	$0	$1,495	3.43	$587	$0	$587	$464	$1,495
13	51444	174	8	VC	1968	Grouting	$12	$0	$2,622	3.43	$1,030	$0	$1,030	$949	$2,622
14	19105	246	8	VC	1975	Grouting	$12	$0	$7,098	3.43	$2,788	$0	$2,788	$3,427	$7,098
15	58571	342	8	VC	1966	Grouting	$12	$0	$4,546	3.43	$1,785	$0	$1,785	$1,489	$4,546
16	18434	127	8	VC	1971	No Action	$0	$0	$2,619	2.27	$1,826	$0	$1,826	$1,084	$2,619
17	852	202	8	VC	1980	No Action	$0	$0	$8,530	2.27	$5,945	$0	$5,945	$4,853	$8,530
18	58769	268	8	VC	1973	No Action	$0	$0	$6,625	2.27	$4,617	$0	$4,617	$2,970	$6,625
19	58798	295	8	VC	1973	No Action	$0	$0	$7,292	2.27	$5,083	$0	$5,083	$3,269	$7,292
20	19261	351	8	VC	1979	No Action	$0	$0	$13,750	2.27	$9,583	$0	$9,583	$7,586	$13,750
21	212	188	8	VC	1985	No Action	$0	$0	$10,288	1.07	$10,105	$0	$10,105	$6,740	$10,288
22	44827	215	8	VC	1982	No Action	$0	$0	$10,728	1.07	$10,537	$0	$10,537	$6,474	$10,728
23	51386	30	8	VC	1984	No Action	$0	$0	$1,623	1.07	$1,594	$0	$1,594	$1,035	$1,623
24	51462	170	8	VC	1980	No Action	$0	$0	$7,179	1.07	$7,051	$0	$7,051	$4,084	$7,179
25	5041025	65	8	VC	1987	No Action	$0	$0	$3,736	1.07	$3,669	$0	$3,669	$2,577	$3,736
	Total	4,250						$19,377	$109,085	2.30	$94,168		$113,545	$99,962	$154,074

Table F.5: Estimated asset values in year 5 (5-year investment plan 3)

Available Fund = $28,365

(1) No.	(2) FSN	(3) Length (ft)	(4) Size (in)	(5) Material	(6) Year	(7) M & R Alternative	(8) Unit Cost ($/LF)	(9) M & R Cost	(10) Base Value	(11) Rating	(12) Deteriorated Value	(13) Expected Added Value	(14) Deteriorated Value =(12)+(13)	(15) Book Value	(16) Modified Approach
1	51115	54	8	VC	1965	No Action	$0	$0	$684	1.05	$3,102	$0	$3,102	$3,343	$3,826
2	39249	78	8	VC	1962	No Action	$0	$0	$887	1.05	$4,480	$0	$4,480	$4,753	$5,426
3	57459	123	8	VC	1962	No Action	$0	$0	$1,399	1.03	$7,098	$0	$7,098	$7,495	$8,557
4	57966	143	8	VC	1962	No Action	$0	$0	$1,627	1.03	$8,252	$0	$8,252	$8,714	$9,948
5	14520	333	8	VC	1968	No Action	$0	$0	$5,017	1.02	$19,301	$0	$19,301	$21,107	$24,395
6	14783	16	8	VC	1968	No Action	$0	$0	$241	1.07	$515	$0	$515	$556	$714
7	58572	67	8	VC	1966	No Action	$0	$0	$891	1.07	$2,132	$0	$2,132	$2,256	$2,870
8	51488	117	8	VC	1966	Sliplining	$30	$3,457	$1,555	4.64	$141	$3,457	$3,598	$3,940	$5,012
9	51938	193	8	VC	1966	Sliplining	$30	$5,703	$2,566	4.64	$233	$5,703	$5,936	$6,499	$8,268
10	51507	298	8	VC	1966	Sliplining	$30	$8,805	$3,961	4.64	$360	$8,805	$9,165	$10,034	$12,766
11	59279	37	8	VC	1987	No Action	$0	$0	$2,127	2.27	$1,328	$0	$1,328	$1,867	$2,127
12	51474	118	8	VC	1965	Grouting	$12	$1,395	$1,495	3.54	$544	$1,237	$1,781	$1,833	$1,495
13	51444	174	8	VC	1968	Grouting	$12	$2,056	$2,622	3.54	$954	$1,824	$2,778	$2,960	$2,622
14	19105	246	8	VC	1975	Grouting	$12	$2,907	$7,098	3.54	$2,583	$2,579	$5,162	$6,212	$7,098
15	58571	342	8	VC	1966	Grouting	$12	$4,042	$4,546	3.54	$1,655	$3,585	$5,240	$5,453	$4,546
16	18434	127	8	VC	1971	No Action	$0	$0	$2,619	2.35	$1,792	$0	$1,792	$1,039	$2,619
17	852	202	8	VC	1980	No Action	$0	$0	$8,530	2.35	$5,837	$0	$5,837	$4,706	$8,530
18	58769	268	8	VC	1973	No Action	$0	$0	$6,625	2.35	$4,533	$0	$4,533	$2,856	$6,625
19	58798	295	8	VC	1973	No Action	$0	$0	$7,292	2.35	$4,990	$0	$4,990	$3,143	$7,292
20	19261	351	8	VC	1979	No Action	$0	$0	$13,750	2.35	$9,409	$0	$9,409	$7,349	$13,750
21	212	188	8	VC	1985	No Action	$0	$0	$10,288	1.09	$10,052	$0	$10,052	$6,563	$10,288
22	44827	215	8	VC	1982	No Action	$0	$0	$10,728	1.09	$10,482	$0	$10,482	$6,289	$10,728
23	51386	30	8	VC	1984	No Action	$0	$0	$1,623	1.09	$1,585	$0	$1,585	$1,007	$1,623
24	51462	170	8	VC	1980	No Action	$0	$0	$7,179	1.09	$7,014	$0	$7,014	$3,961	$7,179
25	5041025	65	8	VC	1987	No Action	$0	$0	$3,736	1.09	$3,650	$0	$3,650	$2,512	$3,736
	Total	4,250						$28,365	$109,085	2.20	$112,023		$139,213	$126,446	$172,039

Appendix G: Asset Values Based on 10-Year Investment Plan

Table G.1: Estimated asset values in year 1 (10-year investment plan)

Available Fund = $7,379

(1) No.	(2) FSN	(3) Length (ft)	(4) Size (in)	(5) Material	(6) Year	(7) M & R Alternative	(8) Unit Cost ($/LF)	(9) M & R Cost	(10) Base Value	(11) Rating	(12) Deteriorated Value	(13) Expected Added Value	(14) Deteriorated Value =(12)+(13)	(15) Book Value	(16) Modified Approach
1	51115	54	8	VC	1965	Pipe Bursting	$58	$3,142	$684	5	$0	$3,142	$3,142	$3,390	$3,826
2	39249	78	8	VC	1962	Pipe Bursting	$58	$0	$887	5	$0	$0	$0	$275	$887
3	57459	123	8	VC	1962	Pipe Bursting	$58	$0	$1,399	5	$0	$0	$0	$434	$1,399
4	57966	143	8	VC	1962	Pipe Bursting	$58	$0	$1,627	5	$0	$0	$0	$505	$1,627
5	14520	333	8	VC	1968	Pipe Bursting	$58	$0	$5,017	5	$0	$0	$0	$2,076	$5,017
6	14783	16	8	VC	1968	Sliplining	$30	$473	$241	4.14	$52	$473	$524	$573	$714
7	58572	67	8	VC	1966	Sliplining	$30	$1,980	$891	4.14	$191	$1,980	$2,171	$2,317	$2,870
8	51488	117	8	VC	1966	Sliplining	$30	$0	$1,555	4.14	$333	$0	$333	$590	$1,555
9	51938	193	8	VC	1966	Sliplining	$30	$0	$2,566	4.14	$550	$0	$550	$973	$2,566
10	51507	298	8	VC	1966	Sliplining	$30	$0	$3,961	4.14	$849	$0	$849	$1,503	$3,961
11	59279	37	8	VC	1987	Grouting	$12	$437	$2,127	3.05	$1,034	$388	$1,422	$2,014	$2,127
12	51474	118	8	VC	1965	Grouting	$12	$0	$1,495	3.05	$727	$0	$727	$541	$1,495
13	51444	174	8	VC	1968	Grouting	$12	$0	$2,622	3.05	$1,275	$0	$1,275	$1,085	$2,622
14	19105	246	8	VC	1975	Grouting	$12	$0	$7,098	3.05	$3,452	$0	$3,452	$3,794	$7,098
15	58571	342	8	VC	1966	Grouting	$12	$0	$4,546	3.05	$2,211	$0	$2,211	$1,724	$4,546
16	18434	127	8	VC	1971	No Action	$0	$0	$2,619	2.06	$1,928	$0	$1,928	$1,219	$2,619
17	852	202	8	VC	1980	No Action	$0	$0	$8,530	2.06	$6,279	$0	$6,279	$5,294	$8,530
18	58769	268	8	VC	1973	No Action	$0	$0	$6,625	2.06	$4,877	$0	$4,877	$3,313	$6,625
19	58798	295	8	VC	1973	No Action	$0	$0	$7,292	2.06	$5,368	$0	$5,368	$3,646	$7,292
20	19261	351	8	VC	1979	No Action	$0	$0	$13,750	2.06	$10,122	$0	$10,122	$8,297	$13,750
21	212	188	8	VC	1985	No Action	$0	$0	$10,288	1.02	$10,247	$0	$10,247	$7,273	$10,288
22	44827	215	8	VC	1982	No Action	$0	$0	$10,728	1.02	$10,685	$0	$10,685	$7,029	$10,728
23	51386	30	8	VC	1984	No Action	$0	$0	$1,623	1.02	$1,616	$0	$1,616	$1,119	$1,623
24	51462	170	8	VC	1980	No Action	$0	$0	$7,179	1.02	$7,150	$0	$7,150	$4,456	$7,179
25	5041025	65	8	VC	1987	No Action	$0	$0	$3,736	1.02	$3,721	$0	$3,721	$2,770	$3,736
	Total	4,250						$6,032	$109,085	3.05	$72,668		$78,651	$66,210	$114,680

Table G.2: Estimated asset values in year 2 (10-year investment plan)

Available Fund = $8,726

(1) No.	(2) FSN	(3) Length (ft)	(4) Size (in)	(5) Material	(6) Year	(7) M & R Alternative	(8) Unit Cost ($/LF)	(9) M & R Cost	(10) Base Value	(11) Rating	(12) Deteriorated Value	(13) Expected Added Value	(14) Deteriorated Value =(12)+(13)	(15) Book Value	(16) Modified Approach
1	51115	54	8	VC	1965	No Action	$0	$0	$684	1.02	$3,130	$0	$3,130	$3,378	$3,826
2	39249	78	8	VC	1962	Pipe Bursting	$58	$4,539	$887	5	$0	$4,539	$4,539	$4,799	$5,426
3	57459	123	8	VC	1962	Pipe Bursting	$58	$0	$1,399	5	$0	$0	$0	$410	$1,399
4	57966	143	8	VC	1962	Pipe Bursting	$58	$0	$1,627	5	$0	$0	$0	$477	$1,627
5	14520	333	8	VC	1968	Pipe Bursting	$58	$0	$5,017	5	$0	$0	$0	$1,990	$5,017
6	14783	16	8	VC	1968	No Action	$0	$0	$241	1.02	$522	$0	$522	$568	$714
7	58572	67	8	VC	1966	No Action	$0	$0	$891	1.02	$2,162	$0	$2,162	$2,302	$2,870
8	51488	117	8	VC	1966	Sliplining	$30	$3,457	$1,555	4.30	$273	$3,457	$3,730	$4,020	$5,012
9	51938	193	8	VC	1966	Sliplining	$30	$0	$2,566	4.30	$450	$0	$450	$929	$2,566
10	51507	298	8	VC	1966	Sliplining	$30	$0	$3,961	4.30	$695	$0	$695	$1,434	$3,961
11	59279	37	8	VC	1987	No Action	$0	$0	$2,127	2.06	$1,402	$0	$1,402	$1,977	$2,127
12	51474	118	8	VC	1965	Grouting	$12	$0	$1,495	3.18	$679	$0	$679	$515	$1,495
13	51444	174	8	VC	1968	Grouting	$12	$0	$2,622	3.18	$1,190	$0	$1,190	$1,040	$2,622
14	19105	246	8	VC	1975	Grouting	$12	$0	$7,098	3.18	$3,223	$0	$3,223	$3,672	$7,098
15	58571	342	8	VC	1966	Grouting	$12	$0	$4,546	3.18	$2,064	$0	$2,064	$1,646	$4,546
16	18434	127	8	VC	1971	No Action	$0	$0	$2,619	2.13	$1,894	$0	$1,894	$1,174	$2,619
17	852	202	8	VC	1980	No Action	$0	$0	$8,530	2.13	$6,166	$0	$6,166	$5,147	$8,530
18	58769	268	8	VC	1973	No Action	$0	$0	$6,625	2.13	$4,789	$0	$4,789	$3,198	$6,625
19	58798	295	8	VC	1973	No Action	$0	$0	$7,292	2.13	$5,272	$0	$5,272	$3,521	$7,292
20	19261	351	8	VC	1979	No Action	$0	$0	$13,750	2.13	$9,940	$0	$9,940	$8,060	$13,750
21	212	188	8	VC	1985	No Action	$0	$0	$10,288	1.03	$10,203	$0	$10,203	$7,095	$10,288
22	44827	215	8	VC	1982	No Action	$0	$0	$10,728	1.03	$10,639	$0	$10,639	$6,844	$10,728
23	51386	30	8	VC	1984	No Action	$0	$0	$1,623	1.03	$1,609	$0	$1,609	$1,091	$1,623
24	51462	170	8	VC	1980	No Action	$0	$0	$7,179	1.03	$7,119	$0	$7,119	$4,332	$7,179
25	5041025	65	8	VC	1987	No Action	$0	$0	$3,736	1.03	$3,705	$0	$3,705	$2,705	$3,736
	Total	4,250						$7,996	$109,085	2.66	$77,126		$85,122	$72,325	$122,676

Table G.3: Estimated asset values in year 3 (10-year investment plan)

Available Fund = $8,110

(1) No.	(2) FSN	(3) Length (ft)	(4) Size (in)	(5) Material	(6) Year	(7) M & R Alternative	(8) Unit Cost ($/LF)	(9) M & R Cost	(10) Base Value	(11) Rating	(12) Deteriorated Value	(13) Expected Added Value	(14) Deteriorated Value =(12)+(13)	(15) Book Value	(16) Modified Approach
1	51115	54	8	VC	1965	No Action	$0	$0	$684	1.03	$3,116	$0	$3,116	$3,366	$3,826
2	39249	78	8	VC	1962	No Action	$0	$0	$887	1.02	$4,521	$0	$4,521	$4,784	$5,426
3	57459	123	8	VC	1962	Pipe Bursting	$58	$7,157	$1,399	5	$0	$7,157	$7,157	$7,543	$8,557
4	57966	143	8	VC	1962	Pipe Bursting	$58	$0	$1,627	5	$0	$0	$0	$449	$1,627
5	14520	333	8	VC	1968	Pipe Bursting	$58	$0	$5,017	5	$0	$0	$0	$1,903	$5,017
6	14783	16	8	VC	1968	No Action	$0	$0	$241	1.03	$520	$0	$520	$564	$714
7	58572	67	8	VC	1966	No Action	$0	$0	$891	1.03	$2,153	$0	$2,153	$2,287	$2,870
8	51488	117	8	VC	1966	No Action	$0	$0	$1,555	1.02	$3,715	$0	$3,715	$3,993	$5,012
9	51938	193	8	VC	1966	Sliplining	$30	$0	$2,566	4.30	$450	$0	$450	$885	$2,566
10	51507	298	8	VC	1966	Sliplining	$30	$0	$3,961	4.30	$695	$0	$695	$1,366	$3,961
11	59279	37	8	VC	1987	No Action	$0	$0	$2,127	2.13	$1,377	$0	$1,377	$1,941	$2,127
12	51474	118	8	VC	1965	Grouting	$12	$0	$1,495	3.31	$632	$0	$632	$490	$1,495
13	51444	174	8	VC	1968	Grouting	$12	$0	$2,622	3.31	$1,108	$0	$1,108	$994	$2,622
14	19105	246	8	VC	1975	Grouting	$12	$0	$7,098	3.31	$3,001	$0	$3,001	$3,549	$7,098
15	58571	342	8	VC	1966	Grouting	$12	$0	$4,546	3.31	$1,922	$0	$1,922	$1,568	$4,546
16	18434	127	8	VC	1971	No Action	$0	$0	$2,619	2.20	$1,859	$0	$1,859	$1,129	$2,619
17	852	202	8	VC	1980	No Action	$0	$0	$8,530	2.20	$6,055	$0	$6,055	$5,000	$8,530
18	58769	268	8	VC	1973	No Action	$0	$0	$6,625	2.20	$4,703	$0	$4,703	$3,084	$6,625
19	58798	295	8	VC	1973	No Action	$0	$0	$7,292	2.20	$5,177	$0	$5,177	$3,395	$7,292
20	19261	351	8	VC	1979	No Action	$0	$0	$13,750	2.20	$9,761	$0	$9,761	$7,823	$13,750
21	212	188	8	VC	1985	No Action	$0	$0	$10,288	1.05	$10,155	$0	$10,155	$6,918	$10,288
22	44827	215	8	VC	1982	No Action	$0	$0	$10,728	1.05	$10,589	$0	$10,589	$6,659	$10,728
23	51386	30	8	VC	1984	No Action	$0	$0	$1,623	1.05	$1,602	$0	$1,602	$1,063	$1,623
24	51462	170	8	VC	1980	No Action	$0	$0	$7,179	1.05	$7,086	$0	$7,086	$4,208	$7,179
25	5041025	65	8	VC	1987	No Action	$0	$0	$3,736	1.05	$3,688	$0	$3,688	$2,641	$3,736
	Total	4,250						$7,157	$109,085	2.41	$83,884		$91,041	$77,601	$129,833

Table G.4: Estimated asset values in year 4 (10-year investment plan)

Available Fund = $8,332

(1) No.	(2) FSN	(3) Length (ft)	(4) Size (in)	(5) Material	(6) Year	(7) M & R Alternative	(8) Unit Cost ($/LF)	(9) M & R Cost	(10) Base Value	(11) Rating	(12) Deteriorated Value	(13) Expected Added Value	(14) Deteriorated Value =(12)+(13)	(15) Book Value	(16) Modified Approach
1	51115	54	8	VC	1965	No Action	$0	$0	$684	1.05	$3,102	$0	$3,102	$3,355	$3,826
2	39249	78	8	VC	1962	No Action	$0	$0	$887	1.03	$4,501	$0	$4,501	$4,768	$5,426
3	57459	123	8	VC	1962	No Action	$0	$0	$1,399	1.02	$7,129	$0	$7,129	$7,519	$8,557
4	57966	143	8	VC	1962	Pipe Bursting	$58	$8,321	$1,627	5	$0	$8,321	$8,321	$8,742	$9,948
5	14520	333	8	VC	1968	Pipe Bursting	$58	$0	$5,017	5	$0	$0	$0	$1,817	$5,017
6	14783	16	8	VC	1968	No Action	$0	$0	$241	1.05	$518	$0	$518	$560	$714
7	58572	67	8	VC	1966	No Action	$0	$0	$891	1.05	$2,143	$0	$2,143	$2,271	$2,870
8	51488	117	8	VC	1966	No Action	$0	$0	$1,555	1.03	$3,699	$0	$3,699	$3,966	$5,012
9	51938	193	8	VC	1966	Sliplining	$30	$0	$2,566	4.43	$365	$0	$365	$840	$2,566
10	51507	298	8	VC	1966	Sliplining	$30	$0	$3,961	4.43	$563	$0	$563	$1,298	$3,961
11	59279	37	8	VC	1987	No Action	$0	$0	$2,127	2.20	$1,352	$0	$1,352	$1,904	$2,127
12	51474	118	8	VC	1965	Grouting	$12	$0	$1,495	3.43	$587	$0	$587	$464	$1,495
13	51444	174	8	VC	1968	Grouting	$12	$0	$2,622	3.43	$1,030	$0	$1,030	$949	$2,622
14	19105	246	8	VC	1975	Grouting	$12	$0	$7,098	3.43	$2,788	$0	$2,788	$3,427	$7,098
15	58571	342	8	VC	1966	Grouting	$12	$0	$4,546	3.43	$1,785	$0	$1,785	$1,489	$4,546
16	18434	127	8	VC	1971	No Action	$0	$0	$2,619	2.27	$1,826	$0	$1,826	$1,084	$2,619
17	852	202	8	VC	1980	No Action	$0	$0	$8,530	2.27	$5,945	$0	$5,945	$4,853	$8,530
18	58769	268	8	VC	1973	No Action	$0	$0	$6,625	2.27	$4,617	$0	$4,617	$2,970	$6,625
19	58798	295	8	VC	1973	No Action	$0	$0	$7,292	2.27	$5,083	$0	$5,083	$3,269	$7,292
20	19261	351	8	VC	1979	No Action	$0	$0	$13,750	2.27	$9,583	$0	$9,583	$7,586	$13,750
21	212	188	8	VC	1985	No Action	$0	$0	$10,288	1.07	$10,105	$0	$10,105	$6,740	$10,288
22	44827	215	8	VC	1982	No Action	$0	$0	$10,728	1.07	$10,537	$0	$10,537	$6,474	$10,728
23	51386	30	8	VC	1984	No Action	$0	$0	$1,623	1.07	$1,594	$0	$1,594	$1,035	$1,623
24	51462	170	8	VC	1980	No Action	$0	$0	$7,179	1.07	$7,051	$0	$7,051	$4,084	$7,179
25	5041025	65	8	VC	1987	No Action	$0	$0	$3,736	1.07	$3,669	$0	$3,669	$2,577	$3,736
	Total	4,250						$8,321	$109,085	2.31	$89,570		$97,891	$84,042	$138,154

Table G.5: Estimated asset values in year 5 (10-year investment plan)

Available Fund = $7,389

(1) No.	(2) FSN	(3) Length (ft)	(4) Size (in)	(5) Material	(6) Year	(7) M & R Alternative	(8) Unit Cost ($/LF)	(9) M & R Cost	(10) Base Value	(11) Rating	(12) Deteriorated Value	(13) Expected Added Value	(14) Deteriorated Value =(12)+(13)	(15) Book Value	(16) Modified Approach
1	51115	54	8	VC	1965	No Action	$0	$0	$684	1.07	$3,086	$0	$3,086	$3,343	$3,826
2	39249	78	8	VC	1962	No Action	$0	$0	$887	1.05	$4,480	$0	$4,480	$4,753	$5,426
3	57459	123	8	VC	1962	No Action	$0	$0	$1,399	1.03	$7,098	$0	$7,098	$7,495	$8,557
4	57966	143	8	VC	1962	No Action	$0	$0	$1,627	1.02	$8,288	$0	$8,288	$8,714	$9,948
5	14520	333	8	VC	1968	Pipe Bursting	$58	$0	$5,017	5	$0	$0	$0	$1,730	$5,017
6	14783	16	8	VC	1968	No Action	$0	$0	$241	1.07	$515	$0	$515	$556	$714
7	58572	67	8	VC	1966	No Action	$0	$0	$891	1.07	$2,132	$0	$2,132	$2,256	$2,870
8	51488	117	8	VC	1966	No Action	$0	$0	$1,555	1.05	$3,682	$0	$3,682	$3,940	$5,012
9	51938	193	8	VC	1966	Sliplining	$30	$5,703	$2,566	4.54	$293	$5,703	$5,995	$6,499	$8,268
10	51507	298	8	VC	1966	Sliplining	$30	$0	$3,961	4.54	$452	$0	$452	$1,229	$3,961
11	59279	37	8	VC	1987	No Action	$0	$0	$2,127	2.27	$1,328	$0	$1,328	$1,867	$2,127
12	51474	118	8	VC	1965	Grouting	$12	$1,395	$1,495	3.54	$544	$1,237	$1,781	$1,833	$1,495
13	51444	174	8	VC	1968	Grouting	$12	$0	$2,622	3.54	$954	$0	$954	$904	$2,622
14	19105	246	8	VC	1975	Grouting	$12	$0	$7,098	3.54	$2,583	$0	$2,583	$3,304	$7,098
15	58571	342	8	VC	1966	Grouting	$12	$0	$4,546	3.54	$1,655	$0	$1,655	$1,411	$4,546
16	18434	127	8	VC	1971	No Action	$0	$0	$2,619	2.35	$1,792	$0	$1,792	$1,039	$2,619
17	852	202	8	VC	1980	No Action	$0	$0	$8,530	2.35	$5,837	$0	$5,837	$4,706	$8,530
18	58769	268	8	VC	1973	No Action	$0	$0	$6,625	2.35	$4,533	$0	$4,533	$2,856	$6,625
19	58798	295	8	VC	1973	No Action	$0	$0	$7,292	2.35	$4,990	$0	$4,990	$3,143	$7,292
20	19261	351	8	VC	1979	No Action	$0	$0	$13,750	2.35	$9,409	$0	$9,409	$7,349	$13,750
21	212	188	8	VC	1985	No Action	$0	$0	$10,288	1.09	$10,052	$0	$10,052	$6,563	$10,288
22	44827	215	8	VC	1982	No Action	$0	$0	$10,728	1.09	$10,482	$0	$10,482	$6,289	$10,728
23	51386	30	8	VC	1984	No Action	$0	$0	$1,623	1.09	$1,585	$0	$1,585	$1,007	$1,623
24	51462	170	8	VC	1980	No Action	$0	$0	$7,179	1.09	$7,014	$0	$7,014	$3,961	$7,179
25	5041025	65	8	VC	1987	No Action	$0	$0	$3,736	1.09	$3,650	$0	$3,650	$2,512	$3,736
	Total	4,250						$7,097	$109,085	2.20	$96,435		$103,375	$89,258	$143,857

Table G.6: Estimated asset values in year 6 (10-year investment plan)

Available Fund = $7,671

(1) No.	(2) FSN	(3) Length (ft)	(4) Size (in)	(5) Material	(6) Year	(7) M & R Alternative	(8) Unit Cost ($/LF)	(9) M & R Cost	(10) Base Value	(11) Rating	(12) Deteriorated Value	(13) Expected Added Value	(14) Deteriorated Value =(12)+(13)	(15) Book Value	(16) Modified Approach
1	51115	54	8	VC	1965	No Action	$0	$0	$684	1.09	$3,070	$0	$3,070	$3,331	$3,826
2	39249	78	8	VC	1962	No Action	$0	$0	$887	1.07	$4,458	$0	$4,458	$4,738	$5,426
3	57459	123	8	VC	1962	No Action	$0	$0	$1,399	1.05	$7,065	$0	$7,065	$7,471	$8,557
4	57966	143	8	VC	1962	No Action	$0	$0	$1,627	1.03	$8,252	$0	$8,252	$8,686	$9,948
5	14520	333	8	VC	1968	Pipe Bursting	$58	$0	$5,017	5	$0	$0	$0	$1,644	$5,017
6	14783	16	8	VC	1968	No Action	$0	$0	$241	1.09	$512	$0	$512	$552	$714
7	58572	67	8	VC	1966	No Action	$0	$0	$891	1.09	$2,121	$0	$2,121	$2,241	$2,870
8	51488	117	8	VC	1966	No Action	$0	$0	$1,555	1.03	$3,699	$0	$3,699	$3,913	$5,012
9	51938	193	8	VC	1966	No Action	$0	$0	$2,566	1.02	$5,972	$0	$5,972	$6,455	$8,268
10	51507	298	8	VC	1966	Sliplining	$30	$0	$3,961	4.64	$360	$0	$360	$1,161	$3,961
11	59279	37	8	VC	1987	No Action	$0	$0	$2,127	2.35	$1,304	$0	$1,304	$1,831	$2,127
12	51474	118	8	VC	1965	No Action	$0	$0	$1,495	2.06	$1,756	$0	$1,756	$1,807	$1,495
13	51444	174	8	VC	1968	Grouting	$12	$2,056	$2,622	3.65	$882	$1,824	$2,706	$2,915	$2,622
14	19105	246	8	VC	1975	Grouting	$12	$2,907	$7,098	3.65	$2,389	$2,579	$4,968	$6,089	$7,098
15	58571	342	8	VC	1966	Grouting	$12	$0	$4,546	3.65	$1,530	$0	$1,530	$1,332	$4,546
16	18434	127	8	VC	1971	No Action	$0	$0	$2,619	2.42	$1,760	$0	$1,760	$994	$2,619
17	852	202	8	VC	1980	No Action	$0	$0	$8,530	2.42	$5,731	$0	$5,731	$4,559	$8,530
18	58769	268	8	VC	1973	No Action	$0	$0	$6,625	2.42	$4,451	$0	$4,451	$2,741	$6,625
19	58798	295	8	VC	1973	No Action	$0	$0	$7,292	2.42	$4,899	$0	$4,899	$3,018	$7,292
20	19261	351	8	VC	1979	No Action	$0	$0	$13,750	2.42	$9,238	$0	$9,238	$7,112	$13,750
21	212	188	8	VC	1985	No Action	$0	$0	$10,288	1.11	$9,998	$0	$9,998	$6,386	$10,288
22	44827	215	8	VC	1982	No Action	$0	$0	$10,728	1.11	$10,425	$0	$10,425	$6,104	$10,728
23	51386	30	8	VC	1984	No Action	$0	$0	$1,623	1.11	$1,577	$0	$1,577	$979	$1,623
24	51462	170	8	VC	1980	No Action	$0	$0	$7,179	1.11	$6,976	$0	$6,976	$3,837	$7,179
25	5041025	65	8	VC	1987	No Action	$0	$0	$3,736	1.11	$3,631	$0	$3,631	$2,448	$3,736
	Total	4,250						$4,964	$109,085	2.05	$102,054		$106,457	$92,341	$143,857

Table G.7: Estimated asset values in year 7 (10-year investment plan)

Available Fund = $10,087

(1) No.	(2) FSN	(3) Length (ft)	(4) Size (in)	(5) Material	(6) Year	(7) M & R Alternative	(8) Unit Cost ($/LF)	(9) M & R Cost	(10) Base Value	(11) Rating	(12) Deteriorated Value	(13) Expected Added Value	(14) Deteriorated Value =(12)+(13)	(15) Book Value	(16) Modified Approach
1	51115	54	8	VC	1965	No Action	$0	$0	$684	1.11	$3,054	$0	$3,054	$3,319	$3,826
2	39249	78	8	VC	1962	No Action	$0	$0	$887	1.09	$4,435	$0	$4,435	$4,722	$5,426
3	57459	123	8	VC	1962	No Action	$0	$0	$1,399	1.07	$7,030	$0	$7,030	$7,447	$8,557
4	57966	143	8	VC	1962	No Action	$0	$0	$1,627	1.05	$8,214	$0	$8,214	$8,658	$9,948
5	14520	333	8	VC	1968	Pipe Bursting	$58	$0	$5,017	5	$0	$0	$0	$1,557	$5,017
6	14783	16	8	VC	1968	No Action	$0	$0	$241	1.11	$510	$0	$510	$548	$714
7	58572	67	8	VC	1966	No Action	$0	$0	$891	1.11	$2,109	$0	$2,109	$2,225	$2,870
8	51488	117	8	VC	1966	No Action	$0	$0	$1,555	1.05	$3,682	$0	$3,682	$3,886	$5,012
9	51938	193	8	VC	1966	No Action	$0	$0	$2,566	1.03	$5,946	$0	$5,946	$6,410	$8,268
10	51507	298	8	VC	1966	Sliplining	$30	$8,805	$3,961	4.88	$116	$8,805	$8,921	$9,898	$12,766
11	59279	37	8	VC	1987	No Action	$0	$0	$2,127	2.42	$1,280	$0	$1,280	$1,794	$2,127
12	51474	118	8	VC	1965	No Action	$0	$0	$1,495	2.13	$1,725	$0	$1,725	$1,781	$1,495
13	51444	174	8	VC	1968	No Action	$0	$0	$2,622	2.06	$2,669	$0	$2,669	$2,870	$2,622
14	19105	246	8	VC	1975	No Action	$0	$0	$7,098	2.06	$4,899	$0	$4,899	$5,967	$7,098
15	58571	342	8	VC	1966	Grouting	$12	$0	$4,546	3.76	$1,411	$0	$1,411	$1,254	$4,546
16	18434	127	8	VC	1971	No Action	$0	$0	$2,619	2.49	$1,728	$0	$1,728	$948	$2,619
17	852	202	8	VC	1980	No Action	$0	$0	$8,530	2.49	$5,626	$0	$5,626	$4,412	$8,530
18	58769	268	8	VC	1973	No Action	$0	$0	$6,625	2.49	$4,370	$0	$4,370	$2,627	$6,625
19	58798	295	8	VC	1973	No Action	$0	$0	$7,292	2.49	$4,810	$0	$4,810	$2,892	$7,292
20	19261	351	8	VC	1979	No Action	$0	$0	$13,750	2.49	$9,070	$0	$9,070	$6,875	$13,750
21	212	188	8	VC	1985	No Action	$0	$0	$10,288	1.14	$9,941	$0	$9,941	$6,208	$10,288
22	44827	215	8	VC	1982	No Action	$0	$0	$10,728	1.14	$10,366	$0	$10,366	$5,919	$10,728
23	51386	30	8	VC	1984	No Action	$0	$0	$1,623	1.14	$1,568	$0	$1,568	$951	$1,623
24	51462	170	8	VC	1980	No Action	$0	$0	$7,179	1.14	$6,937	$0	$6,937	$3,713	$7,179
25	5041025	65	8	VC	1987	No Action	$0	$0	$3,736	1.14	$3,610	$0	$3,610	$2,383	$3,736
	Total	4,250						$8,805	$109,085	1.96	$105,104		$113,909	$99,265	$152,662

Table G.8: Estimated asset values in year 8 (10-year investment plan)

Available Fund = $8,661

(1) No.	(2) FSN	(3) Length (ft)	(4) Size (in)	(5) Material	(6) Year	(7) M & R Alternative	(8) Unit Cost ($/LF)	(9) M & R Cost	(10) Base Value	(11) Rating	(12) Deteriorated Value	(13) Expected Added Value	(14) Deteriorated Value =(12)+(13)	(15) Book Value	(16) Modified Approach
1	51115	54	8	VC	1965	No Action	$0	$0	$684	1.14	$3,036	$0	$3,036	$3,307	$3,826
2	39249	78	8	VC	1962	No Action	$0	$0	$887	1.11	$4,411	$0	$4,411	$4,707	$5,426
3	57459	123	8	VC	1962	No Action	$0	$0	$1,399	1.09	$6,993	$0	$6,993	$7,423	$8,557
4	57966	143	8	VC	1962	No Action	$0	$0	$1,627	1.07	$8,173	$0	$8,173	$8,630	$9,948
5	14520	333	8	VC	1968	Pipe Bursting	$58	$0	$5,017	5	$0	$0	$0	$1,471	$5,017
6	14783	16	8	VC	1968	No Action	$0	$0	$241	1.14	$507	$0	$507	$543	$714
7	58572	67	8	VC	1966	No Action	$0	$0	$891	1.14	$2,097	$0	$2,097	$2,210	$2,870
8	51488	117	8	VC	1966	No Action	$0	$0	$1,555	1.07	$3,663	$0	$3,663	$3,859	$5,012
9	51938	193	8	VC	1966	No Action	$0	$0	$2,566	1.05	$5,918	$0	$5,918	$6,366	$8,268
10	51507	298	8	VC	1966	No Action	$0	$0	$3,961	1.02	$8,885	$0	$8,885	$9,829	$12,766
11	59279	37	8	VC	1987	No Action	$0	$0	$2,127	2.49	$1,257	$0	$1,257	$1,757	$2,127
12	51474	118	8	VC	1965	No Action	$0	$0	$1,495	2.20	$1,694	$0	$1,694	$1,755	$1,495
13	51444	174	8	VC	1968	No Action	$0	$0	$2,622	2.13	$2,621	$0	$2,621	$2,825	$2,622
14	19105	246	8	VC	1975	No Action	$0	$0	$7,098	2.13	$4,811	$0	$4,811	$5,845	$7,098
15	58571	342	8	VC	1966	Grouting	$12	$4,042	$4,546	3.96	$1,339	$3,585	$4,925	$5,218	$4,546
16	18434	127	8	VC	1971	No Action	$0	$0	$2,619	2.59	$1,686	$0	$1,686	$903	$2,619
17	852	202	8	VC	1980	No Action	$0	$0	$8,530	2.59	$5,490	$0	$5,490	$4,265	$8,530
18	58769	268	8	VC	1973	No Action	$0	$0	$6,625	2.59	$4,264	$0	$4,264	$2,513	$6,625
19	58798	295	8	VC	1973	No Action	$0	$0	$7,292	2.59	$4,694	$0	$4,694	$2,766	$7,292
20	19261	351	8	VC	1979	No Action	$0	$0	$13,750	2.59	$8,851	$0	$8,851	$6,638	$13,750
21	212	188	8	VC	1985	No Action	$0	$0	$10,288	1.16	$9,542	$0	$9,542	$6,031	$10,288
22	44827	215	8	VC	1982	No Action	$0	$0	$10,728	1.16	$9,950	$0	$9,950	$5,734	$10,728
23	51386	30	8	VC	1984	No Action	$0	$0	$1,623	1.16	$1,505	$0	$1,505	$923	$1,623
24	51462	170	8	VC	1980	No Action	$0	$0	$7,179	1.16	$6,658	$0	$6,658	$3,589	$7,179
25	5041025	65	8	VC	1987	No Action	$0	$0	$3,736	1.16	$3,465	$0	$3,465	$2,319	$3,736
	Total	4,250						$4,042	$109,085	1.86	$111,512		$115,097	$101,427	$152,662

Table G.9: Estimated asset values in year 9 (10-year investment plan)

Available Fund = $11,998

(1) No.	(2) FSN	(3) Length (ft)	(4) Size (in)	(5) Material	(6) Year	(7) M & R Alternative	(8) Unit Cost ($/LF)	(9) M & R Cost	(10) Base Value	(11) Rating	(12) Deteriorated Value	(13) Expected Added Value	(14) Deteriorated Value =(12)+(13)	(15) Book Value	(16) Modified Approach
1	51115	54	8	VC	1965	No Action	$0	$0	$684	1.16	$3,018	$0	$3,018	$3,296	$3,826
2	39249	78	8	VC	1962	No Action	$0	$0	$887	1.14	$4,386	$0	$4,386	$4,692	$5,426
3	57459	123	8	VC	1962	No Action	$0	$0	$1,399	1.11	$6,955	$0	$6,955	$7,399	$8,557
4	57966	143	8	VC	1962	No Action	$0	$0	$1,627	1.09	$8,130	$0	$8,130	$8,602	$9,948
5	14520	333	8	VC	1968	Pipe Bursting	$58	$0	$5,017	5	$0	$0	$0	$1,384	$5,017
6	14783	16	8	VC	1968	No Action	$0	$0	$241	1.16	$504	$0	$504	$539	$714
7	58572	67	8	VC	1966	No Action	$0	$0	$891	1.16	$2,085	$0	$2,085	$2,195	$2,870
8	51488	117	8	VC	1966	No Action	$0	$0	$1,555	1.09	$3,644	$0	$3,644	$3,832	$5,012
9	51938	193	8	VC	1966	No Action	$0	$0	$2,566	1.07	$5,889	$0	$5,889	$6,322	$8,268
10	51507	298	8	VC	1966	No Action	$0	$0	$3,961	1.03	$8,847	$0	$8,847	$9,761	$12,766
11	59279	37	8	VC	1987	No Action	$0	$0	$2,127	2.59	$1,226	$0	$1,226	$1,721	$2,127
12	51474	118	8	VC	1965	No Action	$0	$0	$1,495	2.27	$1,663	$0	$1,663	$1,730	$1,495
13	51444	174	8	VC	1968	No Action	$0	$0	$2,622	2.20	$2,574	$0	$2,574	$2,780	$2,622
14	19105	246	8	VC	1975	No Action	$0	$0	$7,098	2.20	$4,724	$0	$4,724	$5,722	$7,098
15	58571	342	8	VC	1966	No Action	$0	$0	$4,546	2.06	$4,856	$0	$4,856	$5,139	$4,546
16	18434	127	8	VC	1971	No Action	$0	$0	$2,619	2.68	$1,645	$0	$1,645	$858	$2,619
17	852	202	8	VC	1980	No Action	$0	$0	$8,530	2.68	$5,359	$0	$5,359	$4,118	$8,530
18	58769	268	8	VC	1973	No Action	$0	$0	$6,625	2.68	$4,162	$0	$4,162	$2,399	$6,625
19	58798	295	8	VC	1973	No Action	$0	$0	$7,292	2.68	$4,581	$0	$4,581	$2,640	$7,292
20	19261	351	8	VC	1979	No Action	$0	$0	$13,750	2.68	$8,638	$0	$8,638	$6,401	$13,750
21	212	188	8	VC	1985	No Action	$0	$0	$10,288	1.19	$9,483	$0	$9,483	$5,854	$10,288
22	44827	215	8	VC	1982	No Action	$0	$0	$10,728	1.19	$9,888	$0	$9,888	$5,549	$10,728
23	51386	30	8	VC	1984	No Action	$0	$0	$1,623	1.19	$1,496	$0	$1,496	$895	$1,623
24	51462	170	8	VC	1980	No Action	$0	$0	$7,179	1.19	$6,617	$0	$6,617	$3,465	$7,179
25	5041025	65	8	VC	1987	No Action	$0	$0	$3,736	1.19	$3,444	$0	$3,444	$2,254	$3,736
	Total	4,250						$0	$109,085	1.83	$113,814		$113,814	$99,546	$152,662

Table G.10: Estimated asset values in year 10 (10-year investment plan)

Available Fund = $19,377

(1) No.	(2) FSN	(3) Length (ft)	(4) Size (in)	(5) Material	(6) Year	(7) M & R Alternative	(8) Unit Cost ($/LF)	(9) M & R Cost	(10) Base Value	(11) Rating	(12) Deteriorated Value	(13) Expected Added Value	(14) Deteriorated Value =(12)+(13)	(15) Book Value	(16) Modified Approach
1	51115	54	8	VC	1965	No Action	$0	$0	$684	1.19	$3,000	$0	$3,000	$3,284	$3,826
2	39249	78	8	VC	1962	No Action	$0	$0	$887	1.16	$4,360	$0	$4,360	$4,676	$5,426
3	57459	123	8	VC	1962	No Action	$0	$0	$1,399	1.14	$6,916	$0	$6,916	$7,374	$8,557
4	57966	143	8	VC	1962	No Action	$0	$0	$1,627	1.11	$8,086	$0	$8,086	$8,574	$9,948
5	14520	333	8	VC	1968	Pipe Bursting	$58	$19,377	$5,017	5	$0	$19,377	$19,377	$20,675	$24,395
6	14783	16	8	VC	1968	No Action	$0	$0	$241	1.19	$501	$0	$501	$535	$714
7	58572	67	8	VC	1966	No Action	$0	$0	$891	1.19	$2,072	$0	$2,072	$2,179	$2,870
8	51488	117	8	VC	1966	No Action	$0	$0	$1,555	1.11	$3,625	$0	$3,625	$3,806	$5,012
9	51938	193	8	VC	1966	No Action	$0	$0	$2,566	1.09	$5,858	$0	$5,858	$6,278	$8,268
10	51507	298	8	VC	1966	No Action	$0	$0	$3,961	1.05	$8,805	$0	$8,805	$9,693	$12,766
11	59279	37	8	VC	1987	No Action	$0	$0	$2,127	2.68	$1,197	$0	$1,197	$1,684	$2,127
12	51474	118	8	VC	1965	No Action	$0	$0	$1,495	2.35	$1,633	$0	$1,633	$1,704	$1,495
13	51444	174	8	VC	1968	No Action	$0	$0	$2,622	2.27	$2,527	$0	$2,527	$2,734	$2,622
14	19105	246	8	VC	1975	No Action	$0	$0	$7,098	2.27	$4,638	$0	$4,638	$5,600	$7,098
15	58571	342	8	VC	1966	No Action	$0	$0	$4,546	2.13	$4,769	$0	$4,769	$5,061	$4,546
16	18434	127	8	VC	1971	No Action	$0	$0	$2,619	2.78	$1,606	$0	$1,606	$813	$2,619
17	852	202	8	VC	1980	No Action	$0	$0	$8,530	2.78	$5,231	$0	$5,231	$3,971	$8,530
18	58769	268	8	VC	1973	No Action	$0	$0	$6,625	2.78	$4,063	$0	$4,063	$2,284	$6,625
19	58798	295	8	VC	1973	No Action	$0	$0	$7,292	2.78	$4,472	$0	$4,472	$2,515	$7,292
20	19261	351	8	VC	1979	No Action	$0	$0	$13,750	2.78	$8,433	$0	$8,433	$6,164	$13,750
21	212	188	8	VC	1985	No Action	$0	$0	$10,288	1.21	$9,421	$0	$9,421	$5,676	$10,288
22	44827	215	8	VC	1982	No Action	$0	$0	$10,728	1.21	$9,824	$0	$9,824	$5,364	$10,728
23	51386	30	8	VC	1984	No Action	$0	$0	$1,623	1.21	$1,486	$0	$1,486	$867	$1,623
24	51462	170	8	VC	1980	No Action	$0	$0	$7,179	1.21	$6,574	$0	$6,574	$3,342	$7,179
25	5041025	65	8	VC	1987	No Action	$0	$0	$3,736	1.21	$3,421	$0	$3,421	$2,190	$3,736
	Total	4,250						$19,377	$109,085	1.87	$112,518		$131,896	$117,042	$172,039

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VITA

Hyeon-Shik Baik was born in Seoul, Korea on October 12, 1965. He received his B.S. Degree in Civil Engineering from Hanyang University in Seoul, Korea in 1988. Upon graduation, he pursued a Master's Degree in Civil Engineering, with a Structural Engineering specialty, at Hanyang University in Seoul, Korea in 1990.

After serving as a lieutenant for the Korean Army, he taught at Jeil Technology Institute in Seoul, Korea until he started working for the Seoul Metropolitan Government (the City of Seoul) in 1994. He was the Director of the Department Sewage at Kangdong District, which is one of the 25 Districts in Seoul; the Director of the Department of Facility Management at Han River Management Office; and an assistant director of the Engineering Review Division at the headquarters of the Seoul Metropolitan Government before he left Korea to study abroad in 1999.

He enrolled at Purdue University for a Master's Degree in Civil Engineering, with the specialty of Construction Engineering and Management, in 1999. After obtaining his M.S.C.E. Degree in December 2000, he continued his study to pursue a Ph.D. Degree in Civil Engineering. During his stay at Purdue, he participated in several research projects, including the "Development of a Decision Support System for the Selection of Trenchless Technologies to Minimize the Impact of Utility Construction on Roadways," which was a project funded by the Indiana Department of Transportation (INDOT); and the "Asset Condition Evaluation Techniques for Improved Infrastructure Reporting," which was a project funded by the National Science Foundation (NSF). He received his Ph. D. degree in Civil Engineering from Purdue University in 2003.