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Optimization of Sewer Infrastructure Rehabilitation Planning

by

Colin W. MacLeod

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment
of the requirements for the degree of Master of Science

in

Construction Engineering & Management

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ABSTRACT

Generally most sewer infrastructure systems across North America are in a deteriorating state. Each community has invested a considerable amount into its sewer infrastructure. The physical condition of the sewer infrastructure is not as visibly apparent as other forms of infrastructure and therefore it is difficult to ascertain accurately the physical condition of the system. For this reason many communities repair their sewer infrastructure simply on an emergency basis.

The proactive approach taken in this research was to perform a statistical comparison of the emergency and scheduled costs. The frequency of emergency projects was considered in order to develop an understanding of problematic sewer pipe characteristics. Based on the historical rehabilitation costs and annual budgets, forecasted average unit rehabilitation rates were generated. Finally, linear programming was utilised to facilitate the rehabilitation planning of sewer pipe classes in the order of highest pipe deficiency probability and pipe importance factors.

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CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

The main component of sewer infrastructure is a system of pipes that collects sewage from buildings and storm run-off from the above surface area and distributes the waste to points of treatment or disposal. The construction of sewer systems has greatly improved the standard of sanitation of urban communities as compared to conditions hundreds of years ago. Populations in modern countries depend on sewer infrastructure to enhance their daily lives and may not notice its importance. Citizens in modern communities have no daily interaction with the actual process of sewage transport because it is conveniently transported away underground. This convenient set up of the sewer infrastructure also results in difficulties accessing and determining the physical quality of the system.

In many communities, the issue of sewer system preventative maintenance has been largely neglected. In the City of St. Louis, USA, sewer infrastructure has existed for over 125 years. In 1981 the city was forced to handle an enormous repair bill because of 4,000 sewer collapses (Weil, 1990). The City of Rio de Janeiro, Brazil, is a city that does not use the modern conventional method of sewage treatment, but rather disposes of the sewage four kilometres off the beach into the ocean. In 1999, at some point along the major sewer line, a break occurred and the city had to dispose of the raw sewage much closer to the popular Copacabana and Ipanema beaches, at 64,800 tonnes at a time. The city had to implement a no swim zone and warn residents to stay away from the potentially contaminated beaches. This caused great distress to the city residents and likely a substantial repair bill (Globe and Mail, 1999). In the summer of 1999 the City of Saskatoon, Saskatchewan experienced substantial damage to one of its cherished riverside parks partially due to sewer infrastructure problems. An engineering report concluded that soil erosion blocked a sewer drain which contributed to the saturation of a river bank. The river bank slumped causing major damage to the park's existing infrastructure and the city was left to contend with an estimated $500,000 repair bill (McNairn, 1999).

The previous examples represent the potential problems that improperly maintained sewage infrastructure systems can cause communities. In some instances the integrity of the system can be affected from the start, due to poor construction practices and bad joint seals. In general the sewer infrastructure system as a whole will deteriorate as it ages, due to the rigours of corrosion, abrasion, fatigue and other factors that time contributes. By now most cities have sewer infrastructure systems that have been in place for a long period of time. Investment should be made on an ongoing basis to replace the ageing segments of the infrastructure and not just the minimum needed to repair the annual emergency incidents. An efficient, well planned, proactive rehabilitation strategy will benefit the sewer infrastructure and the residents of the community well into the next century.

1.2 BACKGROUND WORK

Stage I of the Local Sewer Rehabilitation Strategy for the City of Edmonton was completed in June of 1998. The work succeeded in classifying 33 of the different pipe characteristic combinations in the City of Edmonton sewer infrastructure. Based on historical data, a log-linear statistical model was developed that predicted the 'expected deficiency probability' of each sewer pipe class. The expected deficiency probability means that if a particular sewer pipe were to be inspected its likeliness of finding it in a deficient structural state is based on its numeric percentage probability. Based on the inspection of all the predicted deficient pipes, the truly deficient pipes can be identified and their remediation planned for.

1.3 RESEARCH OBJECTIVES

The work performed in Stage I, identified which sewer pipe classifications would likely be in a sufficiently deficient state to the point of required rehabilitative construction. The Local Sewer Rehabilitation Strategy Stage II involved assessment and analysis of the entire local sewer network, excluding sewer services and limited to sewers with diameters of 150mm to 600mm.

The first objective analysed the data from the DRAINS database and determined the total number of pipe classes based on Yang's pipe characteristic combinations in the entire City of Edmonton local sewer system. The next step appointed each section of sewer pipe in the city system (with diameters of 150mm to 600mm) a deficiency probability from the work developed by Yang, 1999. This analysis would help identify what classes of sewer pipe should receive the first inspections. Based on the inspections, the total length and type of deficient pipe can be accounted for. Each section of pipe can then be given a condition rating which has been developed for the City of Edmonton and based on this, can be given a pipe status evaluation of deficient or non-deficient. Figure 1-1 illustrates the development of both stages of the local sewer rehabilitation strategy.

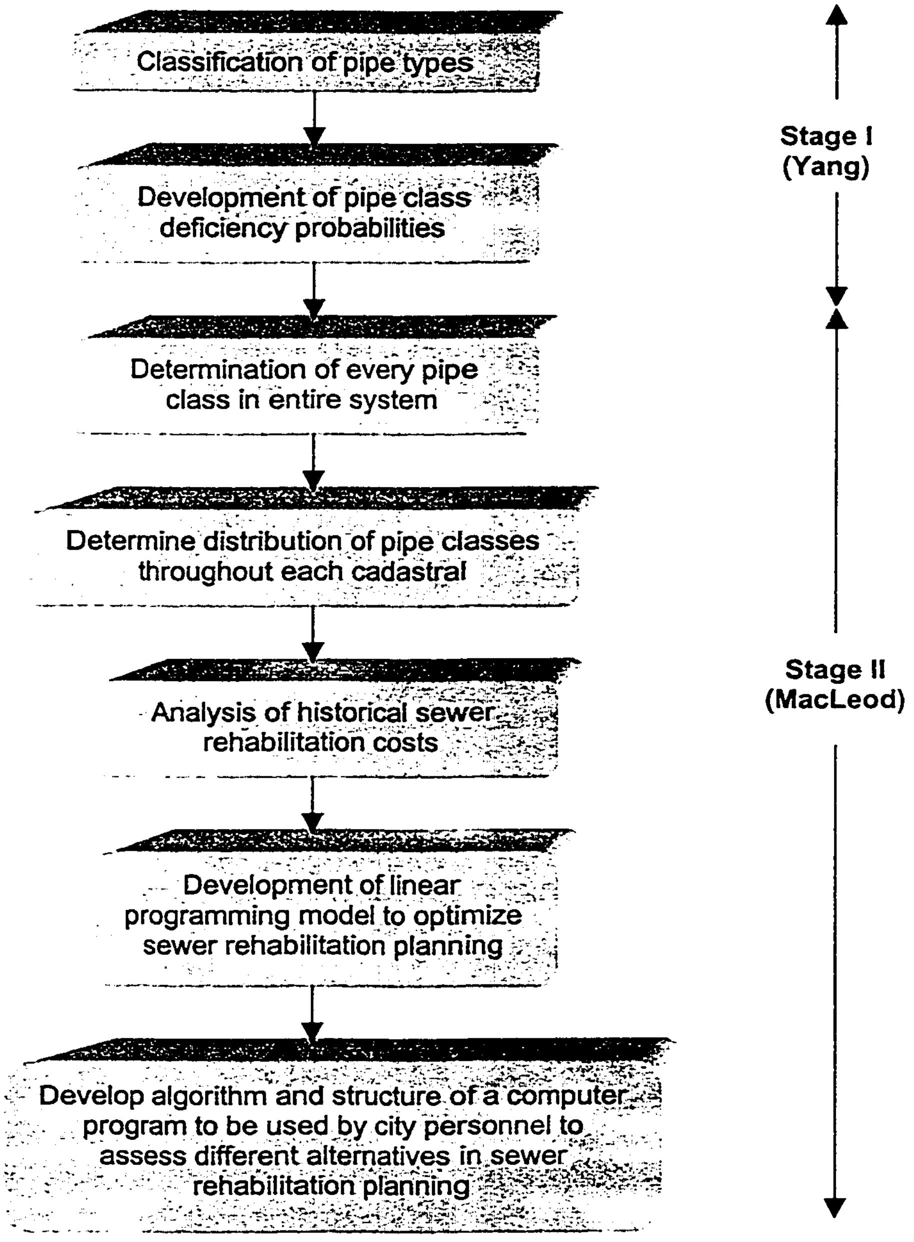


FIGURE 1-1 Stage I and Stage II Sewer Rehabilitation Strategy

The second objective was to collect and analyse the historical rehabilitation costs and associated costs from the City of Edmonton. Based on the analysis, representative unit costs for each rehabilitation alternative could be determined. The statistical distribution of the costs can be analysed. Based on the analysis, the proper unit rate rehabilitation cost can be determined to use within the linear programming model.

The third objective was to develop an algorithm that allows different financial options to take into account varying budgetary and resource constraints to finance the rehabilitation of the deficient pipes in the network. A linear programming strategy will be incorporated as the structure of the model.

The fourth objective was to use the algorithm and data analysis to direct the development of a computer program with a user-friendly interface. The computer program will allow the city engineers to consider different options of rehabilitation and investment for certain pipe classes. The output from the computer program will provide a planning frame to determine the timing for the rehabilitation of each class of pipe together with an associated budget.

The contribution of this research to industry is a proactive methodology for rehabilitation planning. This approach could be applied to other forms of infrastructure such as pavement management, bridges, fresh water distribution systems, oil and gas pipe networks and industrial plants amongst others. The contribution to the academic world is a practical proactive rehabilitation methodology frame that could be manipulated and further developed to meet other research objectives.

1.4 THESIS ORGANIZATION

This thesis consists of six chapters. Chapter 1 is the introduction to the research work and defines its general scope. Chapter 2 is a literature review on linear programming applications and its applicability to a sewer infrastructure system as well as the economic factors that must be considered. The state-of-the-art in sewer inspection techniques is also documented. Chapter 3 describes the methodology of collection and analysis of the sewer infrastructure data and the historical rehabilitation cost data. Chapter 4 explains the development of the linear programming model with the financial outlay options and constraints. Chapter 5 contains the results of the historical cost analysis and the different optimization scenarios. Chapter 6 contains the conclusions and recommendations for further work. Chapter 7 contains the associated reference material.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Modern infrastructure systems are highly developed and considerable capital funding has been invested in them. As the infrastructure grows it also ages. While capital is spent on new infrastructure initiatives, the maintenance of the present infrastructure must not be neglected. Increasingly, public agencies are being urged to develop improved systematic methodology for allotting their period budgets more appropriately so that the capacity of the installed infrastructure is more fully utilised and sustained.

When planning how the investment funds will be allocated, multiple objectives will exist which are dependent on the constraints, resources available for construction, and the interrelationships and dependencies amongst all of the alternatives. This makes the task of planning, prioritizing, and allotting funds complex indeed. It has been noted "public agencies responsible for infrastructure investment are often left to over simplify the elements of the infrastructure investment decision problem. Inefficient use of resources and ignorance or exclusion of certain objectives are commonplace" (Hsieh et al, 1997).

There has been extensive research into financial and decision modelling in pavement management. Many aspects of the research in pavement management have been studied in the formulation of this thesis. The investment into municipal roadways and highway systems is a very expensive undertaking. Because of this, many individuals recognised the need to also invest in research that focused on sustaining the roadway infrastructure at the design standard with appropriate margins of safety while the same time optimizing the associated costs.

The research invested in sewer infrastructure with the focus of longevity and investment optimization has been largely neglected. "Traditionally, owners of underground infrastructure systems have approached the design, construction, maintenance, and operation of sewer systems with a crisis-based approach" (Abraham et al, 1998). This approach to planning of the sewer infrastructure is dangerously risky. A break in a pipe containing sanitary sewer waste can contaminate the surrounding soil media and possibly other areas. A break in a sewer pipe can also cause a backup of sewage into residential basements to the dismay of unsuspecting homeowners.

Mathematical programming is the chosen route of choice for many research initiatives in many practical problems. Provided that the factors and constraints involved in the sewer infrastructure planning problem can be quantitatively mapped into a mathematical program, the problem could be quite effectively analysed and solved.

2.2 PRIORITY RANKING AND OPTIMIZATION

Irrgang and Maze, (1993), performed a survey directed to existing pavement management systems in the United States within each state highway agency. Part of the survey intended to determine what kind of priority ranking criteria each agency used in the allocation of resources to rehabilitation projects and how the optimization model, if any, was set up. The survey results showed that roughly one quarter of state agencies used an optimization model in their pavement management systems. The paper by Irrgang and Maze recommended further study and development of prioritization and optimization models for used in pavement management. The same developmental need can be said for sewer infrastructure.

The survey concluded that four different types of optimization strategies have been employed in pavement management studies. Linear and integer programming are well suited to issues with resource allocation. Incremental benefit-cost and marginal cost-effectiveness differ primarily in their terminology and seek to find the biggest increment of benefit or effectiveness.

TABLE 2-1 Optimization Techniques Used in Pavement Management (Irrgang and Maze, 1993)

Technique	Percentage
Linear Programming	55
Integer Programming	15
Incremental benefit-cost	15
Marginal cost-effectiveness	15

The factors used throughout U.S. state agencies to priority rank projects for rehabilitation in pavement management are listed below, from Irrgang and Maze, (1993). Some of the priority factors used in pavement management can possibly be applied to sewer infrastructure for its own priority ranking scheme.

Priority Factors

Pavement Management	*Sewer Infrastructure*
Pavement distress	
Ride or pavement roughness	
Traffic	Traffic (*Flow Volume*)
Economic factors	Economic factors
Functional class	Functional class
Accidents	
Friction or skid resistance	
Geometric deficiencies	
Structural capacity	Structural capacity
Engineering judgement	Engineering judgement
Age	Age
Location	Location

Some of the constraints used in the optimization models in pavement management can be applied to a sewer infrastructure management optimization model. The following constraints identified in the survey by Irrgang and Maze, (1993), listed in Table 2-2 are useful.

TABLE 2-2 **Possible Constraints Applied to Sewer Infrastructure Optimization Model**

Constraint	**Types and Limitations**
Budget	Can not exceed the one year or multi-year plan
Minimum condition requirement	The overall condition assessment can not pass below the minimum accepted value
Resources	Material, supplies, equipment, contractor limitations
Other	Seasonal allowance of certain construction activities

2.3 EXISTING INFRASTRUCTURE OPTIMIZATION SYSTEMS

The science of mathematical programming has existed for decades. Distinct methodologies have been developed that can be applied to certain problem situations. It is of interest to research how different mathematical programming methodologies have been applied to the realm of infrastructure rehabilitation or maintenance strategies and what variables and constraints were involved. The study of previous research in this area and the complications found using particular methods would be quite useful in developing an effective model to apply to the sewer infrastructure rehabilitation problem at hand.

Jiang and Sinha, (1989), investigated a mathematical optimization technique to incorporate into bridge management systems. A model was desired that could select bridge rehabilitation techniques and allot the necessary budget to manage thousands of state bridges in Indiana in the most financially optimal manner. The chosen mathematical technique was the integration of dynamic programming and zero-one integer linear programming. Markov chain transition probabilities were used as the performance prediction model of each bridge condition throughout the stages of the entire optimization model.

Dynamic programming is a method that can handle a large network of input variables and decisions that must be made. Dynamic programming is capable of finding the optimal solution to the entire network plan and finding the optimal solution to the shorter planning decisions. For example, it can determine the optimal allocation for a 20 year budget and select projects to undertake as well as selecting the annual budgets and projects. When a large network of infrastructure is optimized with too many state and decision variables "then there are computational problems relating to the storage of information as well as the time it takes to perform the computation" (Jiang and Sinha, 1989). Because of this complication, Jiang and Sinha incorporated the use of zero-one integer linear programming.

The optimization model considered by Jiang and Sinha was subject to the following major rehabilitation activities and constrained by the following:

Rehabilitation Activities:

- Deck construction
- Deck replacement
- Bridge replacement

Constraints:

- Available federal budget
- Available state budget

- Maximize system effectiveness of activities for specific year
- No more than one rehabilitation activity can be chosen for one bridge in a specific year
- Zero-one decision variable must be chosen

The dynamic programming was used to consider different possible budget spending combinations while the integer linear programming selected annual projects by determining maximum annual system effectiveness subject to different budget allotments (Jiang and Sinha, 1989). Finally, the dynamic programming model chooses the optimal budget allotment over the entire desired program period while comparing the rehabilitation effectiveness from the integer linear programming analysis.

Although the objective of the model developed by Jiang and Sinha follows that intended for the bridge infrastructure, there is one critical difference in its mathematical set-up. The use of integer programming is restrictive in that some of the designated variables (in this case each specific bridge) must remain integers. That is to say when the model chooses a bridge for a rehabilitation activity in a specific year it must perform the entire rehabilitation in that year and no portion thereof again during the program period. The model cannot perform multiple fractions of rehabilitation on a bridge over multiple years. The zero variable represents a no decision and a one variable represents a yes decision to perform the rehabilitation work in a specific year. In the sewer rehabilitation problem there are a finite number of classes of pipe based on certain characteristics. It is not feasible to restrict an individual class of pipe for rehabilitation only in one year during the program period.

The inspection and rehabilitation work of a certain class of pipe will be partly weighted on its probability of deficiency and since this stochastic assumption weighs heavily in the rating of pipe classification prioritization for rehabilitation, other pipe classes that are highly weighted cannot be disregarded in the annual rehabilitation plan. Therefore multiple fractions of a pipe class should be realistically applied over the program period.

A deterministic dynamic programming optimization model that calculates the optimal maintenance/rehabilitation strategy or minimum life-cycle cost strategy has been developed by Abraham et al, (1998). The planning model is broken up into five year stages, which is the recommended interval of sewer inspections. The planning stages allow for the scheduled time of rehabilitation application. The goal is to maximise the benefit/cost ratio of the maintenance and rehabilitation treatments applied over the planning period of the sewer (50 years was used in the paper) to extend the life of each sewer segment. The model can be made more accurate by incorporating inflation and discount rates and basing them on present value calculations over the life cycle planning period.

The sewer condition rating system used is from the city of Indianapolis. The ratings range from 1 to 5. Sewer segments with a rating of 1 is deemed to be in optimal condition while a segment with a rating of 5 is in critical condition. When a sewer segment has a condition rating of 4 or 5, it is considered to be ready for rehabilitation.

The rehabilitation options are weighed against each other in the optimization model based on established rules. Depending on what type material the pipe is made up of and what kind of waste it is transporting, only certain types of rehabilitation options will be applicable. For example, if the pipe is concrete or brick and shows signs of corrosion, then the shotcrete rehabilitation alternative is ruled out as an alternative (Abraham et al, 1998). The representative unit cost and expected service life of each rehabilitation option explored in the paper are listed in Table 2-3.

TABLE 2-3 Costs and Benefits of Maintenance/Rehabilitation Options (Abraham et al, 1998)

Rehabilitation Option	Cost (US$/m)	Benefit (years)
Do nothing	0	0
Shotcrete	670	20
Cured-in place pipe	1,585	50
Fibreglass reinforced pipe lining	2,270	100
Dig and replace with concrete pipe	1,170 + disruption cost	50
Routine inspection and cleaning, every 5 yr.	17	10-20

The proposed deterministic dynamic programming optimization model by Abraham et al, is unconstrained. The assumption that the annual sewer rehabilitation budget will be unlimited certainly does not reflect the real world of municipal government financial budget scenarios. To alleviate the budget constraint problem, rehabilitation prioritization of certain sewer segments in the city network must be established. The choice of inflation and discount rates, maintenance/rehabilitation unit costs, disruption costs and expected service life amounts will have to be carefully selected since these have a significant impact on the output.

Rehabilitation priority ranking schemes can be classified into four available types besides the use of engineering judgement. Sufficiency ranking, level-of-service deficiency ranking, and incremental benefit-cost analysis calculate a ranking index to sort the projects and allocate funds by order of rank until the budget is exhausted. The most optimal solution is provided by the use of a mathematical programming technique (Razaqpur, 1996).

Razaqpur, (1996), developed a mathematical model designed to allocate available budget for the best bridge replacement and rehabilitation alternative by minimising the system benefit loss and determining the timing of restoration. The model used a combined approach of a neural network to perform single-year optimization and a dynamic programming model to perform the overall multiyear optimization. The author neglected the influence of inflation in the long term planning of budget allotment. The computation time required for the model is long and this only involved two improvement alternatives for each bridge. If the model was applied to a sewer network more than two improvement alternatives exist which would make the computational time possibly longer not to mention the extra computing required the more complex the network becomes.

Karaa et al, (1987), used a linear programming approach to solving a resource allocation problem to rehabilitation and reconstruction of water distribution systems. Based on predictive models for future pipe performance, optimal replacement/rehabilitative action and timing are determined from an analysis of alternatives for each kind of pipe. The model requires that pipes with similar maintenance cost patterns and identical optimal implementation time be pooled together in groups. The linear programming structure of the model then schedules a fraction of each bundle to be implemented for rehabilitation during the planning period.

The model developed by Karaa et al, grouped pipes together which had similar rehabilitation/reconstruction requirements and optimal timing thereof. The model performed the rehabilitation/reconstruction work on only fractions of the pipe groups each year. The pipe groups were supposed to be similar in their optimal scheduling of similar rehabilitative/reconstruction work. The model gave no clear explanation of how the pipe groups were broken up into fractions and prioritized for work commencement in a given year.

Hsieh and Liu, (1997), argue that most exhaustive mathematical programming approaches require too much computational effort to be practical. Hsieh and Liu introduce a financial portfolio investment that is based on replacement heuristics. Linear programming is later used for resource scheduling and the concept of gray relation, is used to determine rank order among alternatives. The numerical example is vaguely explained and their use of only two resource constraints, capital budget and manpower needed during the planning phase is limited.

Millar and Corkum, (1993), performed an interesting study on prioritizing and selecting road paving projects in the province of Nova Scotia. When selecting road paving projects for the upcoming year, there were conflicting prioritized lists and objectives that existed between transportation department managers and politicians. To deal with these conflicting priority lists and a capital budget that restrains the amount of projects that can be completed each year, Millar and Corkum used a goal programming methodology where each project is first evaluated under the following categories:

- Is the project in a specific government party riding or not

- Priority rating of projects by transportation managers/engineers
- Priority rating of projects by government officials
- Length of each paving project
- Relative existing surface condition of each project
- Relative existing ride-ability of each project
- Average annual daily traffic
- Time in years since the relevant road section was last repaved
- Whether the project appeared on a previous priority list or if it is new

The weights used for the category goals were established by using the analytical hierarchy process. The above category goals will not all apply to sewer infrastructure optimization. The methodology used by Miller and Corkum, relied on multiple objectives to differentiate between and optimize. The model pursued for sewer infrastructure will seek to optimize one quantitative objective that is unlike the model developed by Miller and Corkum.

2.4 ECONOMIC ANALYSIS

In many infrastructure projects involving the public and government, the projects have to be planned and accounted for differently than private infrastructure works. Public infrastructure can have an effect on the entire population because they may depend on it for a long period of time. An economic analysis strategy promoted by Szonyi et al, (1989), for public sector projects is the use of the *benefit-cost analysis*. Depending on the nature of the project, certain factors may need to be considered such as:

- Government initial cost of the project
- Government maintenance cost
- Public operational cost
- Public risk cost

The costs of the project will run over a certain planning period. In order to compare the associated costs of each alternative construction strategy, the costs must be dealt with on a level basis such as present worth. The benefit cost mathematical basis for all the factors that are considered follows, from Szonyi et al, (1989).

B_{jt} = public benefits associated with project j during year t
C_{jt} = government costs associated with project j during year t
$t = 0, 1, 2, \ldots n$
i = appropriate interest rate

$$B/C_j(i) = \frac{= \sum_{t=1}^{n} B_{jt}(1+i)^{-t}}{\sum_{t=0}^{n} C_{jt}(1+i)^{-t}}$$

When performing an economic analysis of a public infrastructure project, the interest and discount rate must be carefully chosen. The selection of these rates will have a considerable impact on the calculation of cash flows in the present worth. Szonyi et al, (1989), recommend utilising an interest rate "that is at least as high as the average effective yield on long term government bonds". The interest rate chosen will be affected somewhat by how the government projects are financed and the historical change in costs.

2.5 SEWER INSPECTION

The City of Edmonton Drainage Operations is currently able to inspect 220 km/year of a possible 4400 km of local sewer using the closed circuit television (CCTV) technique (Yang, 1999). It is therefore critical that the inspections are performed on the sections of sewer pipe that are considered to be in the worst potential condition. The inspection techniques used must ensure some degree of reliability so that the capital funding spent on rehabilitation is justified.

The CCTV technique is the most widely used sewer inspection technique today and will remain that way until noticeable improvements are made on other techniques. Stationary CCTV systems are mounted from manholes and have the advantage of not requiring the sewer pipe to be cleaned. The big disadvantage is that they are limited in ability to see down the middle of long sections of pipe. Ground Penetrating Radar (GPR) needs substantial development before it can be used as a reliable inspection technique as it does not perform well in clay soils. Further development will also be needed on the methods of, micro-deflections, natural vibrations, impact echo, and SASW. The advantage of these techniques is that they offer insight into what damage may be occurring on the pipe on the outside, before it can be detected inside the pipe with conventional techniques. The methods that show the most promise to date are the laser and ultrasonic methods because of "their ability to make quantitative measurements of sewer damage" (Makar, 1999). Laser and ultrasonic inspection methods can also be combined with CCTV in different possible combinations in the future to offer significant advantages. Table 2-4 lists sewer inspection techniques used to date and what can be expected from them.

TABLE 2-4 Current Sewer Inspection Techniques (Makar, 1999)

Technique	Where to use	What will be found	Required work
Inspection of inner pipe surface			
Conventional CCTV	Empty pipes; partially filled pipes above the water surface	Surface cracks; visible deformation; missing bricks; some erosion; visual indications of exfiltration/infiltration	None
Stationary CCTV	Pipes with <50m distance between manholes	As CCTV	Studies of concrete and plastic pipe behaviour to determine whether technique can be used in these pipes
Light line CCTV	Pipes where deformation is an issue	Better deformation and CCTV results	Greater accuracy in deformation measurement
Computer assisted CCTV	As CCTV, currently small diameter pipes only	As CCTV, but with quantitative measurements of damage	Extension to larger diameter pipes
Laser scanning	Partially filled pipes; empty pipes	Surface cracks, deformations; missing bricks; erosion losses	Full commercialisation, including field trials
Ultrasound	Flooded pipes; partially filled pipes; empty pipes	Deformation measurements; erosion losses; brick damage	None

Table 2-4 CONTINUED

Inspection of pipe structure and bedding condition			
Microdeflections	Rigid sewer pipes	Overall mechanical strength	Controlled field tests on pipes with known defects
Natural vibrations	Empty sewer pipes	Combined pipe and soil condition; regions of cracking; regions of exfiltration	Studies of effect of bedding materials on results; studies of effects of water inside pipe on results; controlled field tests on pipes with known defects
Impact echo	Larger diameter; rigid sewers	Combined pipe and soil condition; regions of wall cracking; regions of exfiltration	Automated systems for use in small sewers; studies of effect of changes in bedding materials on results; controlled field tests in sewers on pipes with known defects
SASW	Larger diameter; rigid sewers	Regions of wall cracking; overall wall condition; variations in soil condition; regions of exfiltration	Automated systems for use in small sewers; studies of effect of changes in bedding materials on results; controlled field tests in sewers on pipes with known defects
Inspection of bedding			
Ground penetrating radar	Inside empty or partially filled pipes	Voids and objects behind pipe walls; wall delaminations; changes in water content in bedding material	Automated systems for use in small sewers; controlled field tests in sewers on pipes with known defects

2.6 USE OF PAST RESEARCH INITIATIVES

The research performed by Jiang and Sinha, (1989), is an interesting approach for an optimization model directed towards sewer infrastructure instead of bridge infrastructure. The objective function attempts to maximise the system effectiveness of applying rehabilitation activities to certain bridges over the program period. The function depends on developed performance curves for the condition rating of a bridge over time, average daily traffic on a specific bridge, traffic safety, and the impact on the community. The same scope of objective function can be applied to the sewer infrastructure system but incorporating factors that apply more relevantly to the sewer system. The use of integer programming will be attempted but caution will be exercised because of advice from seasoned researchers in the mathematical programming field "Despite decades of extensive research, computational experience with ILP (integer linear programs) has been less than satisfactory. To date, there does not exist an ILP computer code that can solve integer programming problems consistently" (Taha, 1997).

After review of all the mathematical programming techniques available and analysing how they have been applied, the most suitable technique appears to be the classical linear programming because of its successful track record. The objective function could have the same intention of one that maximises the system effectiveness of applying rehabilitation to different pipe classes with varying levels of deficiency probability and importance over a program period. As long as the constraints involved remain linear, the computational success of the model should be positive.

CHAPTER 3

DATA COLLECTION AND ANALYSIS

3.1 INTRODUCTION

The data used in this research was composed of the attributes that make up the actual physical local sewer system of Edmonton. The initial stage consisted of collecting the historical rehabilitation expenditure data. The City of Edmonton Drainage Services compiled certain aspects of each rehabilitation project and kept the data in a database. The rehabilitation projects were the result of planned sewer infrastructure upgrades as well as emergency repairs that had to be completed.

The data used for the prioritization of the entire local sewer system was obtained from the Information Technology Branch of the City of Edmonton. The data was broken up into 37 cadastrals. A cadastral is a location co-ordinate within the gird system of the sewer infrastructure of the City of Edmonton. The data consisted of multiple attributes for each section of pipe in each cadastral. The data was contained in a database until further filtered and tabulated so that it was able to merge with the pipe classifications developed by Yang, (1999). The data can then be used in the linear programming model to develop the rehabilitation and inspection models.

3.2 REHABILITATION COST COLLECTION

The rehabilitation construction cost data was obtained from the City of Edmonton, Drainage Services division. The practice has been to identify projects within the sewer infrastructure that need rehabilitative work. A CCTV inspection is usually performed on the pipes that are suspected of being in poor quality. After the CCTV tape is assessed, the pipe is given a structural condition rating and then the pipe is ranked for treatment within the departments own prioritization process.

The Drainage Services department kept a detailed Excel database of each intended rehabilitation construction project. Before each rehabilitative construction project was implemented, the estimated cost of the particular rehabilitation project was projected. The information for each project was contained as records in the database as well as in the Drainage Services files that most importantly kept the as-built drawings. From these sources the desired data collected was the year of construction, location, cadastral, original construction year, depth, diameter, material, waste type, length, estimated cost, actual cost, emergency or not, and problem definition. The data was then sorted and tabulated for analysis as Figure 3-1 illustrates.

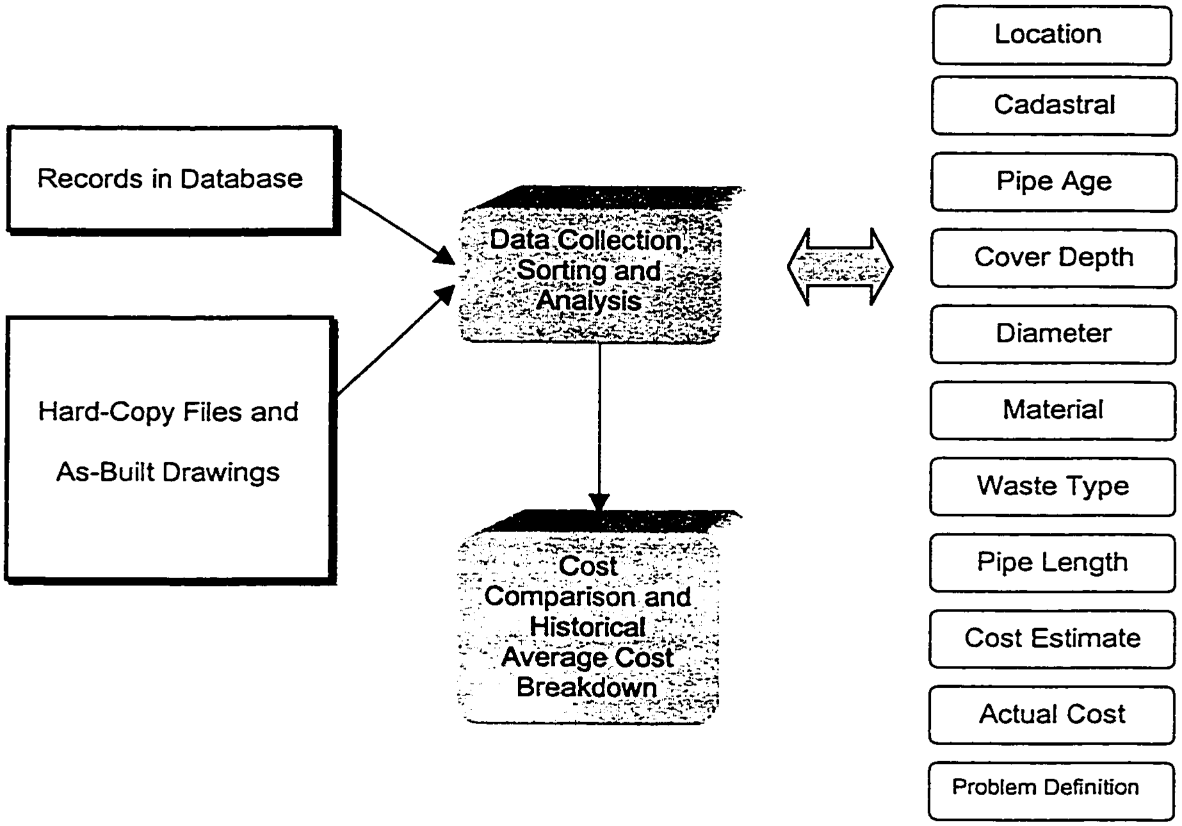


FIGURE 3-1 Historical Cost Collection and Analysis Overview

The data consisted of information on projects dating back to 1989 through to 1999. It was important that each recorded project contained the information on the year of rehabilitation, original year of construction, location, depth, diameter, material, waste type and the estimated cost of rehabilitation. If any of these categories of information were missing for a particular record than the record was discarded in the analysis. The rehabilitation costs of different types of pipes was the focus of the analysis. The database also included projects where work was performed on building new or repairing old manholes, installing culverts, and bank restoration for example. In these types of situations where the work was not performed on sewer pipe rehabilitation the record was also discarded in the analysis.

3.3 REHABILITATION COST ANALYSIS

It was the aim of the cost analysis to determine some kind of relationship between rehabilitation costs for the sewer pipe classifications. The different types of rehabilitation construction methods most commonly applied are:

- Relining
- Open Cut
- Shaft & Tunnel
- Spot Repair

Relining is a technology whose use has increased in popularity more recently. The technology has the advantage that the soil does not have to be excavated. The new line can be inserted from a manhole throughout the length of the deteriorated pipe and then cured into place. The lining has no joints and therefore avoids the problems associated with bad joint connections. Although the technology has only been in use for about 28 years, the technology is said to have a minimum life-span of 50 years. The unit cost associated with relining sewer pipes is quoted at $1/mm diameter for each lineal metre of pipe.

The Open Cut and Spot Repair rehabilitation construction methods usually involve replacing a certain segment of sewer pipe with new pipe. Spot Repairs usually involve replacing 2-3 metres of pipe at a time. Open Cut repairs can involve replacing considerably longer sections of pipe and disturb the local traffic and public. The costs for these methods vary considerably depending on what location of the city the work is performed in and the soil conditions involved.

The Shaft & Tunnel rehabilitation construction method is usually employed only when the sewer pipe needing replacement is 5.2 m below the ground surface. Below 5.2 m it becomes too dangerous to use the Open Cut method and depends on the 'cage' to be effective for safety of the workers. To shore up the trench is more expensive than using the Shaft & Tunnel method to install or replace a sewer pipe. The cost of this method varies with location, soil, and groundwater conditions.

The analysis of the different rehabilitation construction method costs focused on finding the average rehabilitation cost per metre for each construction method. The rehabilitation plan spans over a length of 20 years and it is difficult to determine how the rehabilitation construction technology will change during this time for each of the four methods explained. It is also possible that new sewer rehabilitation technology will enter the market as a major competitive construction methodology. The change in construction technology and the increase or decrease in competition between contractors offering these services, will both influence the associated unit cost of sewer rehabilitation. Each pipe class contains pipe segments that could span over the entire area of the city of Edmonton. It does not seem reasonable to assume that a particular construction method will always be used for a particular pipe class. Based on the location, environmental conditions and many other factors, it is only reasonable to assume the decision to use a certain construction rehabilitation methodology will not remain consistent.

Therefore a general unit cost per lineal metre will be used in the rehabilitation planning of all the pipe classes and twenty year planning period. This general unit cost took into account all the costs from the different rehabilitation techniques over the years that this data was collected and calculated into present worth. The average unit costs for the rehabilitation techniques of relining, open cut and spot repair are also listed with the general unit cost in Table 3-1. Each average unit cost disregarded 10 percent of the high historical costs because those projects were uncommonly expensive. The average unit costs in Table 3-1 contain the construction cost, construction and engineering/design overhead, and contingency cost.

TABLE 3-1 Sewer Rehabilitation Techniques, Historical Costs

General $/m	Reline $/m	Open Cut $/m	Shaft & Tunnel $/m
2,206.48	546.11	3,256.56	5,953.02

Many of the project records were supplemented with a record of the actual cost of the project after construction completion. These actual costs were compared against the estimated costs and the average annual percent difference of estimated costs to actual costs was computed, see Table 3-2. The actual amount of historical emergencies that have occurred on each type of pipe age, size, waste type and material type is shown in Table 3-3. This is compared to the normalised percentage amount of pipe length for each characteristic. Note SAN is sanitary waste, STM is storm waste, and CMB is a combination of sanitary and storm waste. Also note, the material types are defined in Appendix C. The objective of counting the emergency frequency work performed on the different pipe characteristics was to determine if there was some correlation between a certain pipe characteristic and the frequency of emergency work that characteristic holds. The tabulation of emergency frequencies will be correlated against the actual total amount of its pipe characteristic in Chapter 5.

TABLE 3-2 Annual Average Difference in Estimated Costs to Actual Costs

Year	Difference Total Negative = Under Estimation Positive = Over Estimation
1998	-9.78%
1997	1.29%
1996	-5.33%
1995	9.16%
1994	12.00%
1993	11.41%
1992	3.42%

TABLE 3-3 Frequency of Emergency Project Work (Years 1992-98)

Category	% Emergency Frequency	% Total Pipe Length
Age		
0-29	28.9	42.7
30-59	44.7	50.6
60+	26.3	6.7
Size		
150-375	89.0	80.1
450-525	11.0	14.4
550-600	0.0	5.6
Waste		
SAN	52.5	51.7
STM	22.5	31.3
CMB	25.0	17.0
Material		
TP	60.5	49.2
CP	23.7	32.5
CMP	5.3	0.01
PVC	5.3	4.8
ACP	5.3	0.3

3.4 NEW PIPE CLASSIFICATIONS

In 1999, Yang's research used pipe classifications that had pipe diameters ranging in size from 150 to 1050 mm. The local sewer pipe diameter size range has since changed because of a decision by the City of Edmonton to a range of 150 to 600 mm. This meant a decrease in the total lineal amount of pipe that had to be analysed. Yuqing Yang reanalysed her statistical model again to accommodate the change in pipe size range and developed new pipe classifications with the associated expected deficiency probabilities. Thus the number of sewer pipe classifications with corresponding expected probability deficiencies changed from 26 in Yang's research to 33 for this study. The new pipe classifications with the associated expected deficiency probabilities are shown in Table 3-4.

TABLE 3-4 Output of Yang's Deficiency Probabilities

Pipe Class	Age (years)	Diameter (mm)	Material	Waste Type	Ave. Depth of Cover (m)	Deficiency Probability (Observed)	Deficiency Probability (Expected)
1	0-29	450-525	PVC	SAN	6+	100.00	100.00
2	60+	450-525	CP	CMB	0-6	100.00	90.76
3	60+	150-375	CP	CMB	0-6	82.35	82.90
4	30-59	550-600	CP	CMB	6+	100.00	72.85
5	0-29	150-375	TP	SAN	6+	68.42	68.42
6	60+	150-375	NC	CMB	0-6	64.86	64.86
7	60+	150-375	TP	CMB	0-6	64.11	64.00
8	0-29	150-375	TP	SAN	0-6	59.46	59.46
9	0-29	150-375	TP	CMB	0-6	57.14	57.65
10	30-59	150-375	CP	STM	0-6	58.82	54.59
11	30-59	150-375	TP	STM	0-6	54.55	54.55
12	0-29	150-375	TP	CMB	6+	50.00	50.00
13	60+	150-375	PVC	CMB	0-6	50.00	50.00
14	30-59	450-525	CP	CMB	0-6	33.33	45.46
15	30-59	150-375	TP	CMB	0-6	43.86	44.29
16	30-59	450-525	RCP	CMB	0-6	50.00	36.43
17	0-29	150-375	CP	STM	0-6	31.43	33.48
18	0-29	150-375	RCP	SAN	6+	33.33	33.33
19	60+	450-525	TP	CMB	0-6	31.82	31.21
20	30-59	150-375	CP	CMB	0-6	29.41	29.14
21	30-59	150-375	TP	SAN	0-6	28.57	28.57
22	0-29	550-600	CP	STM	0-6	0.00	27.15
23	30-59	550-600	TP	CMB	6+	0.00	27.15
24	0-29	450-525	TP	CMB	0-6	0.00	25.78
25	60+	550-600	TP	CMB	0-6	16.67	23.60
26	0-29	450-525	RCP	STM	0-6	20.00	22.71
27	0-29	550-600	TP	CMB	0-6	100.00	19.13
28	30-59	450-525	CP	STM	0-6	0.00	17.98
29	30-59	450-525	TP	CMB	0-6	21.43	16.87
30	30-59	550-600	TP	CMB	0-6	0.00	12.14
31	0-29	550-600	RCP	STM	0-6	12.50	9.11
32	0-29	450-525	CP	STM	0-6	16.67	8.41
33	30-59	550-600	RCP	CMB	0-6	0.00	5.43

3.5 LOCAL SEWER SYSTEM PRIORITIZATION DATA

3.5.1 Data Organisation and Analysis

The prioritization data consisted of multiple categories of information for each section of local sewer pipe. Some of the cadastral data was previously obtained from the Stage I study but the majority of the data was obtained from Information Technology Branch of the City of Edmonton via compact disk because of the large storage of data required. Once this data was received the data for the entire cadastral sewer system was complete, making up 37 cadastrals. The cadastral files the Construction Engineering & Management group already had in possession and the remaining obtained from the Information Technology Branch are shown in Table 3-5.

TABLE 3-5 Cadastral Files that Make up Entire System

Cadastral Files in Possession	Newly Obtained Cadastral Files	
937+32	943+32	931+24
934+36	943+36	931+40
934+40	943+40	928+24
931+28	940+32	928+28
931+32	940+36	928+32
931+36	940+40	928+40
928+36	940+44	928+44
925+40	937+28	925+24
922+40	937+36	925+28
	937+40	925+32
	937+44	925+36
	934+28	925+44
	934+32	922+32
	934+44	922+36

Once all the data was obtained it was necessary to break up the cadastral information which consisted of thousands of pipe records into individual cadastral files, so as to keep the data as concise and organised as possible. The first step after separating the individual cadastral information was to secure a raw data file for each cadastral that remained original. Each cadastral contained records that were not complete in categories that were required information. In these cases the record was deleted. Therefore the next step was to create a new file that omitted the incomplete files and categories of information that were not pertinent to this study. Each section of sewer pipe was referenced in a very detailed manner by the identification of manhole numbers, upside and downside locations, upside and downside X, Y co-ordinates, and upside and downside cadastrals. The critical categories of information kept in the new processed file were:

- Pipe ID
- Year of Construction
- Pipe Size
- Pipe Material
- Waste Type
- Length
- Manhole From and To
- Upside and Downside Invert
- Upside and Downside Elevation
- Upside and Downside Location
- Upside and Downside X, Y Co-ordinates
- Cadastral

The final file created grouped the pipes into their respective pipe classification categories. The calculation of the age and cover depth was performed in this file. Finally a Macro was written that grouped the pipes into classes, the classes were sorted and the total length of each pipe class for each cadastral was summed. A table showing the distribution of each pipe class in each of the 37 cadastrals is shown in Appendix A. Figure 3-2 illustrates the process of managing the sewer system cadastral files analysis.

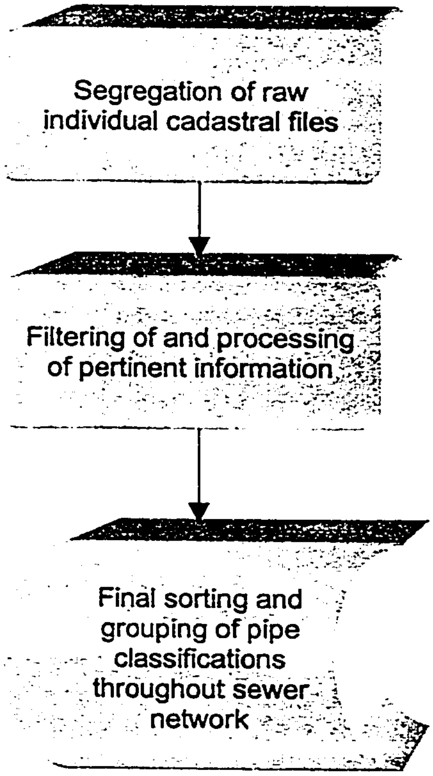


FIGURE 3-2 **Management of Sewer System Cadastral File Analysis**

The results of the sewer system cadastral file analysis determined the distribution of the probable deficient pipes throughout the sewer infrastructure network. The data analysis required that incomplete records were to be eliminated. Therefore it is not expected that the final tally of pipe classes illustrates the exact amount of each pipe class in each cadastral in the City of Edmonton local sewer system. The final database expected to be at a loss of approximately 34 percent of pipe records. This amount was determined by summing the amount of faulty records that had to be eliminated from each cadastral and dividing by the total amount of pipe records that was originally supplied from the Information Technology Branch of the City of Edmonton.

In the analysis of the entire City of Edmonton's local sewer system data, a total of 182 pipe classes were found. The total length of pipe in the pipe class category groupings is shown in Table 3-6.

TABLE 3-6 **Total Length of Pipe in each Pipe Class Sub-Category**

Age Class	Total Pipe (m)	% of Total
0-29	1,071,100.74	42.67%
30-59	1,270,873.58	50.63%
60+	168,167.26	6.70%
Size Class		
150-375	2,009,289.61	80.05%
450-525	360,406.00	14.36%
550-600	140,445.97	5.60%
Material Class		
ACP	6,788.11	0.27%
CIP	2,415.11	0.10%
CMP	320.34	0.01%
CP	816,555.74	32.53%
CPP	525.64	0.02%
FRP	9.91	0.00%
NC	2,831.32	0.11%
PEP	149.04	0.01%
PVC	119,689.60	4.77%
RCP	325,841.12	12.98%
STP	867.95	0.03%
TP	1,234,147.70	49.17%
Waste Class		
CMB	426,731.75	17.00%
SAN	1,297,730.73	51.70%
STM	785,679.10	31.30%
	2,510,141.58	
Depth Class		
0-6	2,330,076.26	92.83%
6+	180,065.32	7.17%

Total Lineal Local Sewer System Pipe = 2,510,141.58 m

During the analysis, the discovery of 182 pipe classes throughout the local sewer system was more than anticipated. The intended analysis required an expected deficiency probability for each pipe class in which there were only 33 provided from Yang's analysis. Yang's analysis considered a sample of five cadastrals in which the pipe record needed an accompanying complete inspection report with a deficiency in order to deem acceptable as a viable record to use in the analysis. The sample of pipe data only covered 5 cadastrals of a possible 37. The inspection reports needed to be complete and are limited to covering 220 km/year of local sewer system. Therefore it is very reasonable that Yang's analysis would not have generated a deficiency probability for each of the 182 pipe classes discovered.

3.5.2 Regrouping of Pipe Classes

There were not 182 pipe class deficiency probabilities generated and they did not necessarily need to be. There are 47 pipe classes where the pipe class occurred in only one cadastral. There are 83 pipe classes that have a total length throughout the entire local sewer system of under 500 lineal metres and 153 pipe classes with less than 10,000 lineal metres. Many of these pipe classes were quite obscure and the use of the uncommon pipe class during the time of construction could have been because of a lack of normal construction material at the time of installation for its intended purpose or many other reasons.

It was decided to keep all the pipe data, which included the obscure pipe classes. In order to treat each pipe class as an established part of the local sewer infrastructure, pipe classes with a small amount of pipe length was combined with other pipe classes of low total length. The systematic approach taken was to combine classes by the three most important pipe class characteristics, which are age, size and waste type.

Two portions of the pipe data were grouped. One group included the main pipe materials used throughout the city sewer infrastructure, which are CP, PVC, RCP, and TP. The other group included uncommon materials used, which are ACP, CIP, CMP, FRP, NC, PEP, and STP. For definition of the preceding abbreviations please refer to Appendix C.

After summing up all the pipe class length totals, it was found that seven of the pipe classes had total lengths of over 100 km. In order to plan for theses large pipe classes easier, it was decided to break up theses pipe classes into total lengths of less than 100 km. This was performed by segmenting the large pipe classes further by age increments. If these large pipe classes had a deficiency probability assigned to them, then all fractions of that pipe class retained the same deficiency probability. The remainder of the pipe classes were ones that had pipe deficiency probabilities allotted to them from Yang's analysis.

Table 3-7 shows the final grouping and segmenting of pipe classes. In summary there are 89 pipe classes. 43 of the pipe classes had established deficiency probabilities. 46 of the pipe classes needed deficiency probabilities and these pipe classes segmented and grouped by common and uncommon construction materials. In the columns of Material and Ave. Depth of Cover, where it says "Variable", this means the pipe class is a conglomeration of other small pipe classes. The full list of all the 182 pipe classes grouped to make the final list of 89 pipe classes is shown in Appendix B.

TABLE 3-7 Final Pipe Class Tally

Pipe Class	Age (years)	Diameter (mm)	Material	Waste Type	Ave. Depth of Cover (m)	Deficiency Probability (Expected)	Length (m)
1	30-33	150-375	TP	SAN	0-6	28.57	79,354.09
2	34-37	150-375	TP	SAN	0-6	28.57	93,589.00
3	38-40	150-375	TP	SAN	0-6	28.57	75,169.50
4	41-42	150-375	TP	SAN	0-6	28.57	74,492.42
5	43-44	150-375	TP	SAN	0-6	28.57	55,501.27
6	45-59	150-375	TP	SAN	0-6	28.57	94,065.52
7	0-21	150-375	TP	SAN	0-6	59.46	85,546.47
8	22-23	150-375	TP	SAN	0-6	59.46	94,376.38
9	24-25	150-375	TP	SAN	0-6	59.46	80,570.56
10	26-29	150-375	TP	SAN	0-6	59.46	94,821.17
11	30-39	150-375	CP	STM	0-6	54.59	82,958.17
12	40-44	150-375	CP	STM	0-6	54.59	93,425.14
13	45-59	150-375	CP	STM	0-6	54.59	84,469.35
14	0-22	150-375	CP	STM	0-6	33.48	75,337.16
15	23-29	150-375	CP	STM	0-6	33.48	84,355.17
16	60-85	150-375	TP	CMB	0-6	64.00	66,037.37
17	86+	150-375	TP	CMB	0-6	64.00	65,346.09
18	30-45	150-375	TP	CMB	0-6	44.29	38,723.34
19	46-59	150-375	TP	CMB	0-6	44.29	77,333.51
20	0-15	150-375	PVC	SAN	0-6	35.95	68,376.25
21	16-29	150-375	PVC	SAN	0-6	35.95	38,110.25
22	30-59	150-375	CP	CMB	0-6	29.14	73,325.79
23	30-59	450-525	CP	STM	0-6	17.98	71,944.77
24	0-29	450-525	RCP	STM	0-6	22.71	61,020.81
25	0-29	150-375	TP	SAN	6+	68.42	51,188.21
26	0-29	450-525	CP	STM	0-6	8.41	50,866.21
27	0-29	550-600	RCP	STM	0-6	9.11	43,275.04
28	30-59	450-525	CP	CMB	0-6	45.46	13,941.76
29	0-29	150-375	RCP	SAN	6+	33.33	12,037.66
30	30-59	450-525	TP	CMB	0-6	16.87	11,640.21
31	30-59	450-525	RCP	CMB	0-6	36.43	7,749.81
32	60+	450-525	TP	CMB	0-6	31.21	7,839.76
33	30-59	550-600	RCP	CMB	0-6	5.43	7,015.84
34	60+	550-600	TP	CMB	0-6	23.60	6,594.31
35	0-29	550-600	CP	STM	0-6	27.15	6,319.13
36	0-29	150-375	TP	CMB	0-6	57.65	4,603.29
37	30-59	150-375	TP	STM	0-6	54.55	3,589.67
38	30-59	550-600	TP	CMB	0-6	12.14	3,225.03
39	60+	150-375	CP	CMB	0-6	82.90	1,362.14
40	60+	150-375	NC	CMB	0-6	64.86	746.09
41	30-59	550-600	TP	CMB	6+	27.15	729.67
42	30-59	550-600	CP	CMB	6+	72.85	308.05
43	0-29	150-375	TP	CMB	6+	50.00	291.79

44	60+	450-525	CP	CMB	0-6	90.76	228.73
45	0-29	450-525	TP	CMB	0-6	25.78	193.85
46	0-29	450-525	Variable	SAN	Variable	35.95	31,966.65
47	0-29	150-375	Variable	SAN	Variable	35.95	58,086.26
48	0-29	150-375	CP	SAN	0-6	35.95	50,261.23
49	30-59	150-375	Variable	SAN	Variable	34.27	73,899.92
50	30-59	450-525	Variable	SAN	Variable	34.27	47,694.55
51	30-59	550-600	Variable	STM	Variable	34.27	38,331.59
52	0-29	150-375	Variable	STM	Variable	35.95	36,686.56
53	0-29	550-600	Variable	SAN	Variable	35.95	12,179.10
54	30-59	550-600	Variable	SAN	Variable	34.27	9,215.79
55	0-29	150-375	Variable	CMB	Variable	35.95	8,486.07
56	60+	150-375	Variable	SAN	Variable	59.56	6,450.53
57	30-59	450-525	Variable	STM	Variable	34.27	36,649.96
58	0-29	450-525	Variable	CMB	Variable	35.95	5,310.49
59	30-59	150-375	Variable	CMB	Variable	34.27	3,852.33
60	30-59	150-375	Variable	STM	Variable	34.27	4,503.23
61	0-29	450-525	Variable	STM	Variable	35.95	4,454.25
62	30-59	450-525	Variable	CMB	Variable	34.27	4,440.10
63	60+	150-375	Variable	CMB	6+	59.56	3,582.02
64	60+	550-600	Variable	CMB	Variable	59.56	3,495.87
65	30-59	550-600	Variable	CMB	Variable	34.27	4,056.22
66	0-29	550-600	Variable	STM	6+	35.95	2,801.87
67	60+	150-375	Variable	STM	Variable	59.56	2,693.22
68	60+	450-525	TP	CMB	6+	59.56	2,430.58
69	0-29	550-600	Variable	CMB	Variable	35.95	2,350.49
70	60+	450-525	Variable	STM	Variable	59.56	417.58
71	60+	550-600	Variable	STM	Variable	59.56	281.63
72	60+	450-525	TP	SAN	Variable	59.56	267.61
73	60+	550-600	TP	SAN	6+	59.56	98.54
74	30-59	150-375	Variable	SAN	Variable	34.27	3,632.78
75	0-29	150-375	Variable	SAN	Variable	35.95	5,642.94
76	30-59	450-525	Variable	SAN	Variable	34.27	987.09
77	30-59	150-375	Variable	CMB	0-6	34.27	646.07
78	0-29	150-375	Variable	STM	0-6	35.95	623.04
79	0-29	150-375	NC	CMB	Variable	35.95	443.77
80	30-59	150-375	Variable	STM	0-6	34.27	402.24
81	0-29	450-525	Variable	STM	Variable	35.95	160.01
82	60+	150-375	Variable	CMB	Variable	59.56	151.64
83	0-29	450-525	PEP	SAN	0-6	35.95	149.04
84	60+	450-525	NC	CMB	0-6	59.56	94.81
85	0-29	550-600	Variable	STM	0-6	35.95	66.91
86	30-59	450-525	NC	CMB	0-6	34.27	54.00
87	30-59	550-600	NC	CMB	0-6	34.27	52.12
88	60+	550-600	NC	CMB	0-6	59.56	48.77
89	30-59	450-525	CMP	STM	0-6	34.27	6.10

The deficiency probabilities assigned to the 46 pipe classes in need were based on their respective age classes. The 33 deficiency probabilities from Yang's analysis were grouped based on their age class and an average deficiency probability was calculated. Table 3-8 shows the deficiency probabilities calculated that was used.

TABLE 3-8 Assigned Deficiency Probabilities

Age 0-29	Age 30-59	Age 60+
35.95	34.27	59.65

The deficiency probability is the principle stochastic factor involved in the establishment of the importance of each pipe class and arranging the data for financial forecasting analysis. Though the allotment of an initial deficiency probability to the pipe classes that need one may be subjective at first, over time more accurate deficiency probabilities can be calculated and used in the updated local sewer system.

3.6 DATA COLLECTION AND STORAGE RECOMMENDATIONS

There are two separate bodies of data that need to be addressed in this research, the local sewer system rehabilitation data and the entire local sewer system infrastructure data. In both cases the practice has been to include most of the pertinent data, but the data entry itself was not validated. The objective of the new data entry system should be to validate the important data fields of the new record in order to maintain the integrity of the database. Once enough information has been compiled on the record under consideration, the database should prompt the user to satisfactorily complete each mandatory data entry field before the record may be inputted into the database.

The following terminology is used in the proceeding sections. A record in a database is analogous to a row in spreadsheet format and a field is analogous to a column in that record.

3.6.1 Local Sewer System Rehabilitation Data

The local sewer rehabilitation database has been managed using an Excel platform. It may be more advisable to manage the database with database software such as the readily available Access. The utilisation of Access will allow the convenient validation of selected data fields and provide many other capable tools for use in other aspects of the data management. Table 3-9 illustrates the fields of data that are currently collected, the newly suggested fields, and the suggested validation rules.

TABLE 3-9 Rehabilitation Database

New Category	Overall Category	Category	Mandatory	Validation Rules
(New)		Pipe_ID	Yes	Valid Choice
		STATUS	Yes	
		LOC #	Yes	
		FILE NAME (LOCATION)	Yes	
(New)		CADASTRAL	Yes	Valid Choice
		DRA/DIST		
		SYSTEM , C=COMB, S=SAN, ST=STM	Yes	Valid Choice
	PRIORITY	#		
		SCORE		
		DRN/NET		
		DATE REFERRAL RECEIVED		
		DATE ACKNOWL SENT		
		DATE ALL INFO RECEIVED		
		PROBLEM DESCRIPTION	Yes	
(New)		LENGTH (M)	Yes	
(New)		OLD DIA (mm)	Yes	
(New)		OLD MATERIAL	Yes	Valid Choice
(New)		NEW DIA (mm)	Yes	
(New)		NEW MATERIAL	Yes	Valid Choice
	COST ESTIMATE	A=ACTUAL, B=BID, P=PRELIM		
		COST O/H NOT INCL.	Yes	
		SPLIT SAN.		
		SPLIT STORM		
(New)		ACTUAL COST		
		ORIG. CONST. YEAR	Yes	
		PROP. CONST. YEAR	Yes	
		PAVING CONFLICT 3-YEAR NO CUT		
		CONT'R/CONSULT		
		DWG #	Yes	
(New)		REHAB. CONSTRUCTION METHOD	Yes	
	STATUS	DESIGN STATUS		
		DESIGN COMPL		
		ISSUED		
		CONSTR START		
		CONSTR COMPL		
		AS BUILTS RECEIVED		
		C.C.C. DATE		
		F.A.C. DATE		
		SERVICE REPORT		
		CC INSP. REPORT		
		FINAL CCTV		
		POSTING ORDER #		
		CENTRAL FILE		
		COMMENTS		

3.6.2 Local Sewer System Infrastructure Data

The entire local sewer system infrastructure data was obtained from the DRAINS database of the City of Edmonton. Not every field of data was relevant to this study and were excluded in the analysis. Table 3-10 shows all the fields of data in the DRAINS database and the relevant fields used in this study. The Validation Rules in Table 3-10 describe how the database should be programmed so that when a new record is entered, there is more insurance that the information is correct.

The 'Last Inspected', 'Last Repaired', and 'Relined or not' fields have been added because this information is important to the engineer in future planning and insuring that inspection work is not redundantly planned on the same section of pipe too soon.

TABLE 3-10 Local Sewer System Database

New	Relevant	Data Field	Validation Rules
	Yes	Pipe_ID	
Last Inspected	Yes		
Last Repaired	Yes		
		UPS_FAC_ID	
		DWS_FAC_ID	
	Yes	UPS_WASTE_TYPE	Only Possible Choices
	Yes	DWS_WASTE_TYPE	Only Possible Choices
	Yes	LENGTH	
	Yes	PIPE_MATERIAL	Only Possible Choices
Relined or not	Yes		
	Yes	PIPE_SIZE	
		BED_CLASS_CODE	
		FLOW_CONDITION_CODE	
	Yes	YEAR_CONSTRUCTED	Valid Possible Range
		PIPE_CLASS_CODE	
		SEGMENT_SLOPE	
		LOCATION_CODE	
		PIPE_REFURBISHED_FLAG	
		REFURB_MATERIAL	
		REFURB_EQUIV_CIRC_DIAMETER	
		REFURB_MAJOR_DIMENSION	
		REFURB_MINOR_DIMENSION	
		FAC_TYPE_CODE	
		FAC_STATUS_CODE	
		PIPE_SPEC_ID	
		CON_REC_ID	
		ASSOC_DETAIL_DRAWING_ID	
	Yes	MH_FR	
	Yes	MH_TO	
	Yes	UPS_INVERT	>DWS_INVERT
	Yes	DWS_INVERT	<UPS_INVERT
	Yes	UPS_ELEV	>DWS_ELEV
	Yes	DWS_ELEV	<UPS_ELEV
	Yes	UPS_LOCATION	
	Yes	DWS_LOCATION	
		UPS_GEO_ADMIN_ID	
		DWS_GEO_ADMIN_ID	
	Yes	UPS_X_M	
	Yes	UPS_Y_M	
	Yes	DWS_X_M	
	Yes	DWS_Y_M	
	Yes	UPS_CADASTRAL	
	Yes	DWS_CADASTRAL	
		UPS_JCT_ID	
		DWS_JCT_ID	
		MSLINK	

3.6.3 Database Relationships

The resulting database will contain two separate bodies, or tables, of information. One table will be the local sewer system rehabilitation data and the other is the local sewer system infrastructure data. The two tables of data will have a relationship in the form that each section of the same pipe will have the same pipe identification number. The linking of the rehabilitation data and infrastructure data is a crucial link in finally establishing a relationship between the two important bodies of data.

It is also important that the database contain only pipe sections that are in use and not pipe sections that have been deactivated but still in the ground. An efficient inspection and planning program should only spend its resources on the sections of pipe that are active and the engineer should readily have that knowledge. Hence, the database should be consistently updated when a new pipe section enters the system or an old pipe section leaves. The collection of the historical rehabilitation data for a particular section of pipe will aid the engineer in future studies of trends and forecast models.

3.7 CONCLUSION

The historical rehabilitation costs were analysed based on what construction technique was used. It was determined that a general average unit rehabilitation construction rate would be used in the 20 year planning strategy for the rehabilitation of the local sewer infrastructure.

The sewer infrastructure data consisted of thousands of records of pipe section information. Approximately 34 percent of the records could not be used in the analysis because they did not include proper information or the information was entered incorrectly. After the filtering the incomplete records a total of 24,004 records were used. The pipe sections were grouped into 89 different kinds of pipe characteristic classes and the total length of each characteristic, the distribution of pipe classes throughout each cadastral was calculated.

CHAPTER 4

LINEAR PROGRAMMING MODEL

4.1 INTRODUCTION

The mathematical programming model used in this research is not a physical model or code for a computer program. This model is a mathematical set of algebraic terms and symbols. The model itself must first be formulated in some descriptive manner that is reasonable and usually can in qualitative terms. The challenge is to translate the problem from qualitative terms to quantitative terms. If this task is performed successfully it becomes a sound mathematical model. The model must be representative of the original problem situation but reasonably cannot be expected to incorporate every aspect and every relationship the real world problem contains. The model must therefore arrive at some results that provide a practical solution to the main factors involved with the real situation. At the same time the modeller concentrates on keeping the model valid of the real situation, the model must also be 'tractable' which means it must be capable of being solved.

Integer '0-1' programming was attempted in the formulation of the model in this research. Upon running the model with essentially the same model structure and objective function as finally used in this research, the result was that the model would not converge on a solution. Efforts were then focused on building the model in a linear programming format.

The chosen frame of mathematical programming is linear programming. Linear programming is defined as a "mathematical modelling technique designed to optimize the usage of limited resources" (Taha, 1997). Linear programming uses linear mathematical expressions and continuous variables. That is to say variables composed in the following expressions would not be linear.

$$x^y \qquad \text{or} \qquad \mathrm{Log}(x)$$

Linear programming is a way of formulating a solution and the possible set of solutions are bounded by the very constraints that are integrated within the problem. Linear programming has developed the reputation and "wide acceptance as one of the most practical tools of operations research" (Jensen, 1986). As long as the constraints and variables involved in the model are linear the computation and analysis should be able to be performed without great difficulty.

4.2 THE SIMPLEX METHOD

The Simplex Method is one of the most utilised tools in operations research for linear programming. Versions of the Simplex Method vary among different computer programs but all versions are built on the same principles. One of the features that make the Simplex Method attractive to use is that of all the feasible solutions that are possible to the problem, only the solutions at the vertex of the bounded region are examined. This makes the computation of finding the optimal solution much easier to arrive at. The Simplex Method is an algebraic procedure for finding the best solution to a system of equations. The tableau and the algebraic methodology can both be employed in the simplex method. The algorithms differ slightly to accommodate their respective forms. The following methodology described is the algebraic method.

For a typical optimization problem, the simplex algorithm requires that the set of equations be translated into equality form rather than an inequality form. Slack variables are utilised and added to the constraint equations to make the inequality equations into equality equations. The slack variables must stay non-negative and any solution to the equality equations must also satisfy the inequality equations. Solutions must be non-negative, and any solution that does not satisfy this condition is eliminated. The following equations demonstrate the set-up of the equations.

$$\text{Maximize } Z = ax_1 + bx_2$$

$$cx_1 - dx_2 \leq e$$

$$fx_1 + gx_2 \leq h$$

Equality Form

Objective Function

$$\begin{array}{llll} \text{Maximize } Z - ax_1 - bx_2 & & = 0 \\ cx_1 + dx_2 + x_3 & & = e \\ fx_1 + gx_2 & +x_4 & = h \\ x_1, x_2, x_3, x_4 & & \geq 0 \end{array}$$

Constraints

x_1, x_2 are variables

x_3, x_4 are slack variables

When the model has more variables than constraints, a finite number of solutions can be expected. One of the first functions at the beginning of the Simplex Method algorithm is to determine the number of variables in the 'basic solution'. The standard linear programming model contains m linear equations with n (unknown) variables. The maximum number of basic solutions is determined by the following equation.

$$\text{Maximum basic solutions} = \frac{n!}{m!(n-m)!}$$

The amount of m linear equations must be less than the amount of n variables, or ($m < n$). The $n - m$ amount of variables are set to zero and then m amount of variables is solved for. The following examples illustrates this.

$$x_1 + 3x_2 + 5x_3 + x_4 + 2x_5 = 9$$

$$3x_1 + x_2 + 6x_3 + x_4 + 7x_5 = 5$$

There are $m = 2$ linear equations and $n = 5$ variables. Calculating $n - m$ yields 3 variables to arbitrarily set to zero, which leaves 2 variables within 2 equations to solve for. If the solution arrives at a unique solution and the variables are non-negative then this is a *basic solution*. The m number of variables (in this case 2) are called the basic variables (or the basis) and the $n - m$ variables (in this case 3) are called the non-basic variables. The algorithm considers each possible basic solution once. A finite number of basic solutions are calculated iteratively until the algorithm arrives on an optimal solution and a feasible bounded region.

The simplex method uses an objective function and its linear constraint equations as the m linear equations and the total amount of variables n throughout the objective function and constraint equations. The starting basic variables in the first iteration can be a random choice or a convenient choice can be to start with the slack variables. The procedure is then to solve for the m basic variables which equal the amount of m constraint equations.

When changing from one adjacent basic solution to another, the variable in the objective equation with the 'most negative' coefficient is chosen as j. A new variable must enter the basis and one of the previous basis variables must exit, to begin the next iteration. The methodology is to divide the right hand side of the equation b_i, by the corresponding non-basic variable y_{ij} (which corresponds to the most negative coefficient in the objective function). This must be performed for each constraint equation with the objective of finding the minimum value amongst the constraint equations.

$$\text{Minimise} \qquad \delta_{ij} = b_i/y_{ij} \qquad\qquad \text{if } y_{ij} > 0$$

The variable with the most negative coefficient in the objective equation enters as the new basis variable. The basis variable in the constraint equation with the minimum δ_{ij} must leave the basis.

The equations must now be transformed into the new simplex form with the new basis variables. The technique used is to take the coefficient of j in the constraint equation with the minimum δ_{ij} and divide the equation by the coefficient, effectively making the coefficient in front of the j variable equal to one. The next step is to take each equation and add it to a multiple of the minimum δ_{ij} equation in order to eliminate each j in the other equations. The resulting addition of the variables for each equation becomes the new transformed equations. Now the new basis variables in the new simplex equations can be solved to find a new basis solution. Before proceeding to the next iteration a test of optimality on the objective equation's coefficients should be performed. If the objective equation form is not optimum, then the iterative process continues until an optimal solution is arrived at. The key stopping rule in the iterative algorithm procedure is to check to determine if there are negative coefficient solutions in the objective function. If there is not, then the solution is optimal and the computations can end.

When changing objective functions from one of maximization or minimization the algorithm remains the same. The change that must be made is one where the all the signs in all the terms of the objective function must be changed to the opposite of what they originally were.

4.3 DETERMINATION OF WEIGHTS FOR PIPE FACTORS

This section explains the pipe importance factors that seem relevant and provides the weights for each category for each pipe factor. Generating pipe importance factor weightings although somewhat subjective, provides another avenue in the analysis to weigh certain pipe classes of more importance over others for inspection and rehabilitation planning when resources are limited. The pipe factor that provides the platform for the analysis is the probability deficiencies provided by Yang, (1999). The other factors that will be considered are the factors due to the waste type, material type, and the size of the pipe.

The weight factors used in this research were determined by a consensus of a good cross-section of experts. These individuals were engineers from the City of Edmonton Design and Construction and Strategic Planning groups as well as input from the academics performing this research.

4.3.1 Effect of Waste Type

Combined pipe carries both sanitary and storm waste. If a blockage in the pipe occurs during a storm it has the highest chance of backup into surrounding building basements, causing potential for health concerns, contamination (although diluted), and property damage. Sanitary pipe carries only sanitary waste. If a blockage in the pipe occurs during a storm it has less of a chance of backup into surrounding building basements than combined pipe but still possible, causing potential for health concerns, contamination and property damage. Storm pipe carries only storm water and other debris and should be considered the least harmful waste. Theoretically storm pipes should not be connected to houses. Table 4-1 lists the waste type pipe weights.

TABLE 4-1 Waste Type Pipe Factors

Waste Type	Ranking	Factor
Combined	1	1
Sanitary	2	0.9
Storm	3	0.5

4.3.2 Effect of Joints in Heavily Treed Locations

PVC pipes typically have lengths of 6.1m between joints and relining technology in effect has no joints. Tile pipe has typical lengths of 1.0 to 1.2m and concrete has typical lengths of 1.0 to 1.4 m, between joints. In heavily treed areas the roots have a better chance of infiltrating a section of pipe with more joints such as the brittle tile pipe and concrete pipe and causing damage and blockage. Therefore it seems only reasonable to assume that tile and concrete pipes should be weighted more importantly than PVC and relined pipes. Although a map does not exist which labels the heavily treed locations in Edmonton, it may be reasonable to weigh tile and concrete pipes slightly greater than PVC and relined pipes.

Unfortunately during the analysis of the local sewer system infrastructure data, it was noticed that the database was not set up to record which sections of pipe had been relined. This aspect was crucial in establishing a weighting factor for the pipe material. Therefore the pipe material weight factor was not incorporated into the pipe importance factor.

4.3.3 Effect of Pipe Size

It was noted in the Standard Sewer Condition Rating System Report that larger diameter pipes should be ranked with greater importance than smaller diameter pipes. This makes sense since the smaller pipes feed into the larger ones, and if a problem exists in a larger pipe the effects are more widely spread throughout the system. Table 4-2 lists the size type pipe weights.

TABLE 4-2 **Size Type Pipe Factors**

Diameter Type	Ranking	Factor
550-600	1	1
450-525	2	0.7
150-375	3	0.5

4.4 LOCAL SEWER SYSTEM MODEL

The linear programming optimization method requires maximisation or minimisation of some objective, called the objective function. A typical objective function is that of a company analysing their operation costs and sales and wishing to maximise their profit. In this study the approach taken is to minimise the capital expenditure during the planning period as well as appointing attention in the form of inspection and rehabilitation in order of the most important pipe classes.

When minimising the capital expenditure, the methodology ensures that the entire annual budget is utilised throughout the entire planning period until all of the required expenditure is completed. In this manner, if for example the required expenditure is five million dollars to rehabilitate the system, the annual budget is one million dollars, and the program planning period is 6 years, then the annual expenditure will be maximised to one million dollars for five years and there will be no expenditure during the sixth year. This way the cost is not distributed over the six years and the loss due to inflation is minimised.

The objective of the inspection and rehabilitation program must not disregard the importance of focusing the attention on the most important pipe classes first. The most important pipe classes are the ones in order of the highest deficiency probabilities and the added effect of the pipe class waste and size weightings. Mathematically this must be incorporated into the objective function. Remembering one of the keys to a successful linear programming model is that the output of the model must in some way be minimised or maximised. In this model part of the objective function was to minimise the effect of inflation growth of capital expenditure. Therefore the approach taken was to make a summation of the deficiency probability, the pipe waste type weighting, and the pipe size weighting. The key characteristic of each pipe class was its deficiency probability. Therefore the deficiency probability was weighted substantially heavier than the influence of the pipe waste type factor and pipe size factor, in developing the Pipe Importance Factor for each pipe class. The deficiency probability was on a scale ten times greater than the scales of the pipe size and waste type factors.

It is of importance to mention here why the classical benefit/cost ratio was not fully utilised as was its use was thoroughly considered as mentioned in the literature review. The benefit/cost ratio is a good tool when comparing different rehabilitative construction methods. In Chapter 3 it was decided that the costs of different rehabilitative construction methods would not be incorporated into the model because of the many uncertain cost factors over a 20 year planning period and one inclusive unit cost would be used. In this way the 'benefit' aspect of the benefit/cost ratio was further explored which developed into the pipe importance factor used in this study.

The summation of the deficiency probability, the waste type factor, the pipe size factor resulted in the pipe importance factor for each pipe class. The pipe importance factor was then incorporated into the annual expenditure cost. The key distinction when incorporating the pipe importance factor is that the number cannot stay constant throughout the 20 year planning period because the linear program model does not recognise the which pipe classes are more important than others. The model cannot minimise a constant number. The pipe importance factor for each pipe class will grow exponentially each year, clearly differentiating between pipe classes with different pipe importance factors. This growth the model recognises and is able to effectively minimise, hence appointing rehabilitation and inspection in order of the largest numeric pipe importance factor.

The annual expenditure cost was the product of the unit rehabilitation cost/per metre, the effective length and the effect of annual interest. The effective length was the product of the total length of pipe for a certain pipe class and its deficiency probability. This is an important distinction because the rehabilitation model plans for the length of pipe in each class that is probably deficient. On contrary the inspection model plans for the total length of each pipe class.

Therefore the unit rehabilitation cost, the effective (or total) length, and the compounded pipe importance factor are summed for each pipe class for each year and then the effect of monetary interest is applied to this annual summation. This annual summation is called the 'Annual System Influence'. The objective function is then the summation of all the annual system influence values throughout the 20 year planning period.

The model is subject to constraints. During the length of the 20 year planning period it is the goal of the model to rehabilitate all the probable deficient pipes in the system and inspect the entire system. The constraint for this goal is that the fraction of rehabilitation or inspection performed for each year (the decision variable), summed over 20 years for each pipe class, must less than or equal to one, representing 100 percent completion. The fraction in any year therefore may be greater than or equal to zero and less than or equal to one. The annual expenditure cost must also be less than or equal to the annual budgetary limit.

When the decision variable is at least some fraction greater than zero, then that fraction of the total effective length of that pipe class is scheduled for rehabilitation. It is assumed that the city engineers will be able to determine which specific portion of the pipe class will receive rehabilitation funding. This may be by means of location prioritization or political agenda.

The following equations show the mathematical development of the objective function and the associated constraints.

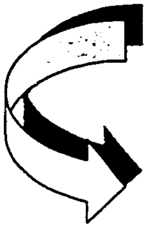
$$\mathrm{Eff}_c = (\text{Total Length}_c)\cdot(\mathrm{DP}_c)$$

$$\mathrm{PIF}_c = (\text{WasteWeight}_\omega) + (\text{SizeWeight}_\alpha) + (\mathrm{DP}_c)$$

$$\mathrm{CPIF}_c = (1 + \mathrm{PIF}_{cy}/100)^y$$

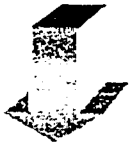
$$\mathrm{ASI}_y = (\ U\cdot\mathrm{Eff}_c\cdot\mathrm{CPIF}_{1\,y}\cdot\delta_{1\,y} + \ldots\ldots\ldots + U\cdot\mathrm{Eff}_{89}\cdot\mathrm{CPIF}_{89\,y}\cdot\delta_{89\,y})\cdot(1+r)^{(y-1)}$$

$$\mathrm{AEy} = (\ U\cdot\mathrm{Eff}_{1\,y}\cdot\delta_{1\,y} + \ldots\ldots\ldots\ldots\ldots + U\cdot\mathrm{Eff}_{89}\cdot\delta_{89\,y})\cdot$$



The Objective Function is then:

$$\text{Minimise} = \mathrm{ASI}_1 + \mathrm{ASI}_2 + \ldots\ldots\ldots\ldots + \mathrm{ASI}_{20}$$



The Constraints:

$$1 \geq \delta_{1\,1} + \delta_{1\,2} + \ldots\ldots\ldots\ldots + \delta_{1\,20}$$

$$\downarrow$$

$$1 \geq \delta_{89\,1} + \delta_{89\,2} + \ldots\ldots\ldots\ldots + \delta_{89\,20}$$

$$AE_y \leq AB_y$$

$$\delta_{1\,1} \ldots\ldots\ldots\ldots \delta_{89\,20} \geq 0$$

Where:

AB_y = Annual Budget

AE_y = Annual Expenditure

ASI_y = Annual System Influence

$CPIF_c$ = Compounded Pipe Importance Factor

DP_c = Deficiency Probability

Eff_c = Effective Length

PIF_c = Pipe Importance Factor

U = Unit Rehabilitation Construction Cost / lineal metre

δ_{cy} = Fraction of rehabilitation or inspection performed (decision variable)

ω = Waste type factor

α = Pipe size factor

c = Specific pipe class

r = Appropriate interest rate

y = Specific year in planning period

4.5 LINEAR PROGRAM SOFTWARE

The linear programming software tool used in this research is called 'Solver'. Solver was developed by Frontline Systems Inc. It is a standard add-on tool feature in Microsoft Excel software. The software is readily compatible with Excel, user friendly, and is easily accessible. This is why it was chosen over any other obscure DOS-based linear programming software. The software is programmed to be able to handle linear and integer programming problems. The simplex method is used with the linear programming problems and the branch and bound method is used for integer programming problems.

The model is laid out on a standard Excel worksheet and cells must be properly connected by formulas so that Solver recognises the logical mathematical relationships. Within the Solver input form the user chooses the cell on the worksheet to naximise, minimise or reach a specified value. The range of cells must be chosen that are called the 'adjustable cells'. These are the cells (or variables) that Solver computes iteratively and adjusts the preliminary values to arrive at an optimum solution. The constraints within the worksheet must be entered by selecting the specific or range of cells subject to logical numeric, or related cells. The entire model can be altered to meet the requirements of the model more appropriately by changing the number of iterations it performs, computational time, precision and tolerance of the solution convergence as well as other factors.

There is a limit on the number of adjustable cells a worksheet can contain. In this model the number of adjustable cells was 89 pipe classes x 20 years in the planning period which equals 1780 adjustable cells. Solver did not have the capability to handle this many adjustable cells on one worksheet so the model was broken up into 20 worksheets. This accommodated the solution of one year in the planning period per worksheet plus the same number of cells needed to carry over the uncompleted fraction of work per pipe class to the next worksheet to solve for the next year. The computational time took approximately 1.7 minutes per worksheet, therefore approximately 34 minutes per 20 year planning period scenario. This was performed on an Intel Pentium II chip, 300 MHz processor PC computer.

Different scenarios were computed with budgetary constraints on the rehabilitation model and inspection model which are further described in Chapter 5.

4.6 CONCLUSION

The optimization model was configured using linear programming. The linear programming software tool used the Simplex Method as the mathematical structure. The objective function and constraints used in the model were linear and therefore the model was successfully optimized. The objective function in the model was to minimise the capital expenditure over the planning period, by still utilising the full annual budgets and minimising the growth of the pipe importance factor for each pipe class. Pipe importance weights for the pipe size and the waste type were chosen after a consensus with Edmonton Drainage Engineering personnel.

CHAPTER 5

ANALYSIS AND RESULTS

5.1 INTRODUCTION

The results of this research determined the order of scheduling rehabilitation and inspection for the 89 different pipe classes. Different approaches to analysing and correlating the historical rehabilitation costs to the various related factors were taken to determine underlying relationships that may not have been clear in the past.

5.2 SENSITIVITY ANALYSIS

In linear programming, the coefficients that are in the objective function or the functions that are directly related to them, can have a major influence on the output of the model. Subjective numeric coefficients can change with time and it is important to understand the reasoning behind the constants used in a model. The coefficients that were subjective in this research were that of the pipe size weights and the waste type weights.

There were 89 pipe classes determined in this research. Yang, 1999, provided 33 pipe classes with deficiency probabilities. These deficiency probabilities were based on all five pipe characteristics, which are age, size, material, waste type, and average cover depth. Seven of these pipe classes needed to be further broken up into smaller pipe classes because their total length was greater than the limit of 100 km. When the seven pipe classes were broken up, it left a total of 43 pipe classes with a unique deficiency probability from Yang's analysis (the pipe classes that were further broken up into smaller pipe classes all shared the same deficiency probability as the pipe class they were derived from).

This left 46 pipe classes that needed a deficiency probability appointed to them. Recalling from Chapter 3, the 0-29 age class had a deficiency probability of 35.95 %, 30-59 age class 34.27%, and the 60+ age class 59.56%. The values were calculated from Yang's 33 deficiency probabilities as an average for each age class. There may be some argument that the natural progression of deficiency probabilities should get higher as the age class gets older. This may be true as far as the time deterioration effect on the pipe is concerned. The slightly higher deficiency probability for the 0-29 age group over the 30-59 age group may serve the rehabilitation priority planning model better in order to detect early structural problems from the result of freeze-thaw cycles and other problems due to faulty construction placement. These occurrences may be more likely to occur early in the pipe section's lifetime as compared to a pipe section that is placed in a very secure position and location.

The 46 pipe classes that were appointed three different values of deficiency probabilities were based on three different age classes. This resulted in many pipe classes having the exact same deficiency probability. The pipe size weight and the waste type weight of each pipe class were added to each deficiency probability to produce a Pipe Importance Factor as seen in the following equation.

$$PIF_c = WasteWeight_\omega + SizeWeight_\alpha + DP_c$$

Where:

DP_c = Deficiency Probability

PIF_c = Pipe Importance Factor

ω = Waste type factor

α = Pipe size factor

c = Specific pipe class

The platform for prioritizing and scheduling rehabilitation and inspection for the most important pipe classes was based on the order of pipe classes with greatest deficiency probability. It was the goal of the Pipe Importance Factor to slightly differentiate pipe classes with the same deficiency probability while not changing this order of pipe class priority and scheduling. The Pipe Importance Factor equation was set up so that the pipe size weight and the waste type weight ranged on a scale of 0 to 1. The deficiency probability ranged on a scale of 0 to 100 to assume its dominance in the equation.

It was evident a sensitivity analysis would be required in order to determine how using different subjective pipe size weights and waste type weights would influence the priority ranking/scheduling of the pipe classes. The sensitivity analysis changed the pipe size and waste type weights from low to high values in different combinations. The technique was to change one the size weight's values from low to high while maintaining the waste weights constant. This was then performed for the waste weight and finally a combination of changing both weights at the same time.

The effect of altering the weights on the Pipe Importance Factor and the scheduling of the rehabilitation and inspection is shown in Figures 5-1. The order was not changed between different values of deficiency probability, only infrequent changes occurred between the order of pipe classes with the same deficiency probability. The pipe size weights and the waste type weights shown in Chapter 4 made up the pipe importance factor values termed the base values.

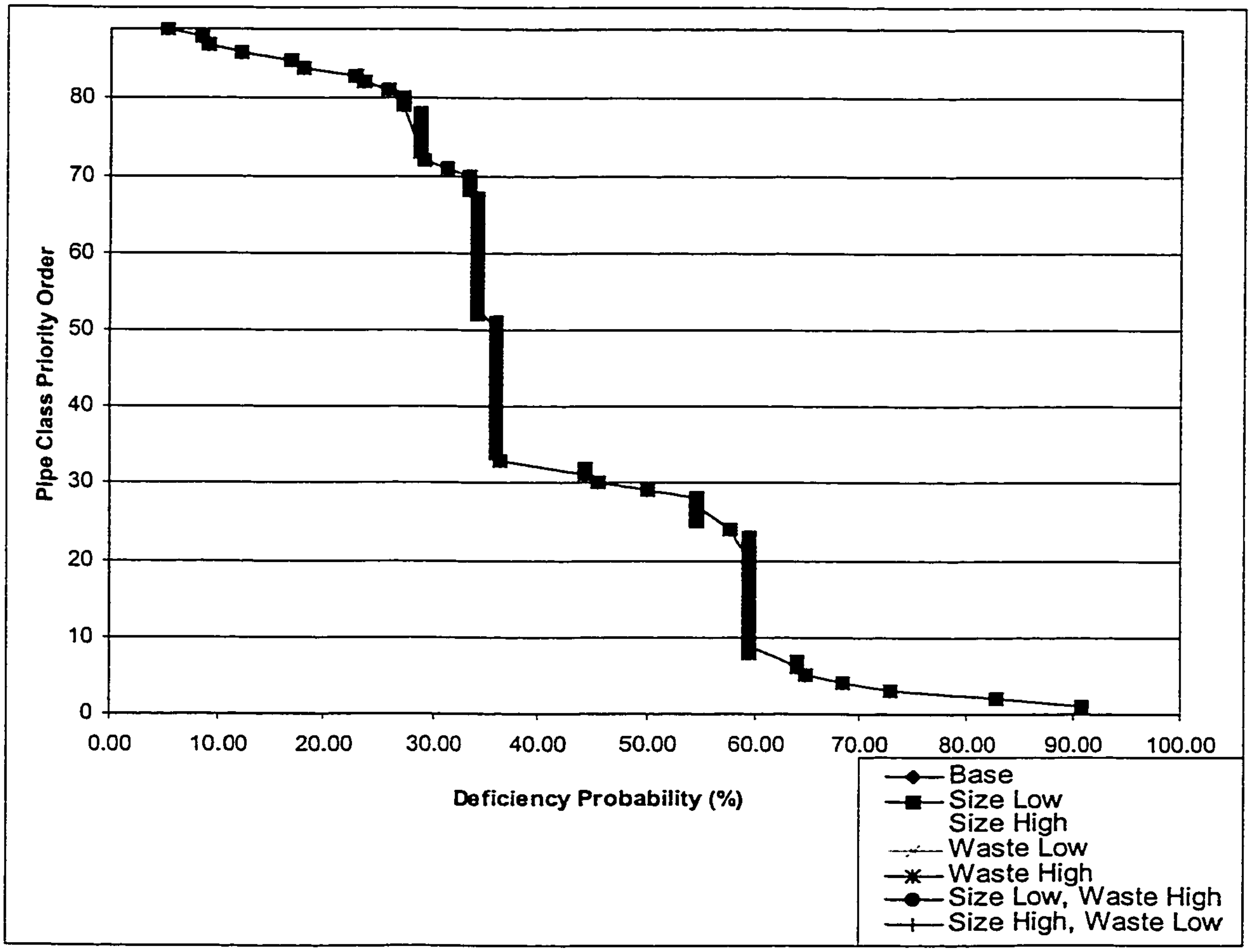


FIGURE 5-1 **Sensitivity Analysis of Pipe Class Priority Order vs. Deficiency Probability**

The mean square error took the difference between the original ordered pipe importance factor for each pipe class due to a change in the pipe importance factor by changing either of the size type or waste type weights. The differences for all the pipe classes were then summed up as shown in the following equation and Table 5-1.

Mean Square Error = $(\Sigma_c((PIF_{original} - PIF_{new})^2))/89$

PIF = Pipe Importance Factor

c = For each respective pipe class

TABLE 5-1 Sensitivity Analysis Weight Combinations and Mean Square Error

Weight Combination	Size Weight			Waste Weight			Mean Square Error
	550-600	450-525	150-375	CMB	SAN	STM	
Base	1	0.7	0.5	1	0.9	0.5	-
Size Low	1	0.5	0.3	1	0.9	0.5	0.03056
Size High	1	0.9	0.8	1	0.9	0.5	0.05551
Waste Low	1	0.7	0.5	1	0.6	0.2	0.05000
Waste High	1	0.7	0.5	1	0.95	0.8	0.02292
Size Low, Waste High	1	0.5	0.3	1	0.95	0.8	0.02000
Size High, Waste Low	1	0.9	0.8	1	0.6	0.2	0.01966

The mean square error was calculated between the base pipe importance factor values for each of the 89 pipe classes and the new combinations. The mean square error was low for each combination and was deemed acceptable, as shown in Table 5-1. This means the weights chosen for the following results and other possible combinations chosen in the future would not alter the priority order of pipe classes with different deficiency probabilities.

5.3 FINANCIAL PLANNING MODELS

Different planning scenarios were performed for the rehabilitation of the local sewer system and inspection of the entire system. The structure of the linear programming remained the same for rehabilitation and inspection except for a couple of differences. The rehabilitation model was optimized based on the effective length of each pipe class and the principle constraint was the annual budgetary constraint. The inspection model was optimized based on the total length of each pipe class and the principle constraint was the annual inspection capability of 220 km/year.

The first sewer rehabilitation model was set up to rehabilitate the effective length of each pipe class in the city. The results of the model indicated that to perform this task over 20 years it would require a substantial capital investment of $2,217,639,092.98 (in present worth). This meant an annual expenditure of $110,881,954.65. The scheduling output of this model can be seen in Appendix D. Obviously an annual budget of $110,881,954.65 for sewer infrastructure investment is highly unlikely of happening, unless the product the sewer pipes carry magically gains some monetary value in the future. Therefore a more realistic approach was clearly needed to determine the annual budget for each year of the 20 year planning period.

The annual budgetary constraint can be influenced by a variety of factors. It is by no means expected that the annual budgetary constraint will remain the same each year. It is a difficult value to predict and it is why financial models remain somewhat dynamic during their planning period because the future budgets can be constantly adjusted.

A possible approach to determining the annual budget over the 20 year planning period, would be using a goal based objective. The objective would be to rehabilitate the effective lengths of the pipe classes with high deficiency probabilities, over a certain cut-off. Table 5-2 lists some possibilities using this approach and the expected costs of each possibility.

TABLE 5-2 Goal Based Approach to Determining Annual Budgets

Deficiency Probability (%)	Effective Length (m)	($/m)	Total Cost ($)	20 year ($/year)
≥ 50.00	491,500.52	2,213.21	1,087,793,865.87	54,389,693.29
≥ 59.56	133,073.15	2,213.21	294,518,826.31	14,725,941.32
≥ 64.00	121,153.53	2,213.21	268,138,204.13	13,406,910.21
≥ 64.86	37,068.11	2,213.21	82,039,511.73	4,101,975.59
≥ 72.85	1,561.22	2,213.21	3,455,307.72	172,765.39

As can be seen in Table 5-2, budgetary requirements are very sensitive to determining the amount of funding needed based on targeting pipe classes over a certain deficiency probability. Each pipe class contains widely varying amounts of infrastructure and this may not be the most appropriate way of determining budget requirements.

The method of determining an annual budgetary constraint that seemed the most reasonable was to derive the future budget values from historical rehabilitation construction budgets. Table 5-3 lists the historical annual rehabilitation construction budgets.

Table 5-3 Historical Annual Rehabilitation Construction Budgets

Year	Historical Budget
1991	800,008.30
1992	1,111,500.00
1993	1,238,800.00
1994	1,063,050.00
1995	2,439,600.00
1996	979,450.00
1997	1,197,000.00
1998	1,225,500.00

The future budgetary values were forecasted using linear regression based on the historical values. The equation used is:

$$\text{Forecasted Budget} = a + bx$$

x = each new year in the 20 year plan

$$a = \underline{Y} - b\underline{X}$$

$$b = \frac{n\Sigma xy - (\Sigma x)(\Sigma y)}{n\Sigma x^2 - (\Sigma x)^2}$$

The forecasted values for the 20 year planning period, started for the year 2000 and ended in the year 2019, shown in Table 5-4.

TABLE 5-4 Forecasted 20 Year Period Rehabilitation Budgets

Year	Forecasted Budget Present Worth
2000	1,519,059.14
2001	1,566,731.07
2002	1,614,402.99
2003	1,662,074.92
2004	1,709,746.85
2005	1,757,418.77
2006	1,805,090.70
2007	1,852,762.63
2008	1,900,434.56
2009	1,948,106.48
2010	1,995,778.41
2011	2,043,450.34
2012	2,091,122.27
2013	2,138,794.19
2014	2,186,466.12
2015	2,234,138.05
2016	2,281,809.98
2017	2,329,481.90
2018	2,377,153.83
2019	2,424,825.76

The output from this more realistic rehabilitation model was based on the forecasted annual budgets and is shown in Appendix E. The pipe classes that were fully and partially rehabilitated are shown in Table 5-5. By basing the 20 year plan on the forecasted budgets, the rehabilitation only comprised 3.64 % of the total effective length of the system. This little percentage of the system is expected when the total forecasted annual budget sum over 20 years is $ 39,438,848.97 as compared to the substantial amount of $2,217,639,092.98 estimated to complete the entire system.

TABLE 5-5 Pipe Classes Completed Using Forecasted Annual Budgets

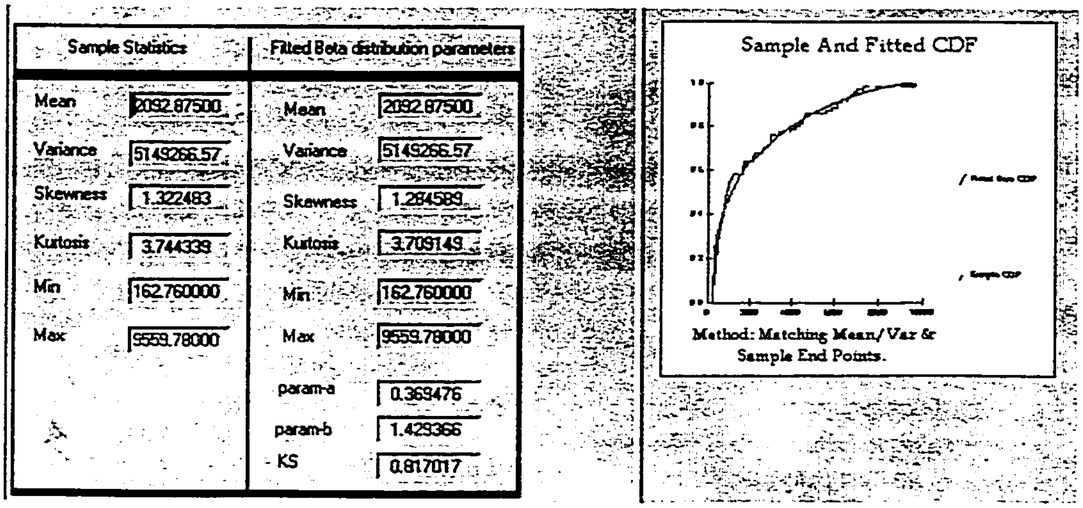
Pipe Class	Effective Length (m)	PIF	% Completed
44	207.60	92.46	100.0
39	1,129.21	84.40	100.0
42	224.41	74.85	100.0
25	35,022.97	69.72	46.6

The entire inspection of the local sewer infrastructure system was modelled and from that model the entire system is expected to be capable of being fully inspected within 12 years and the output of this model is shown in Appendix F.

5.4 REHABILITATION COST ANALYSIS RESULTS

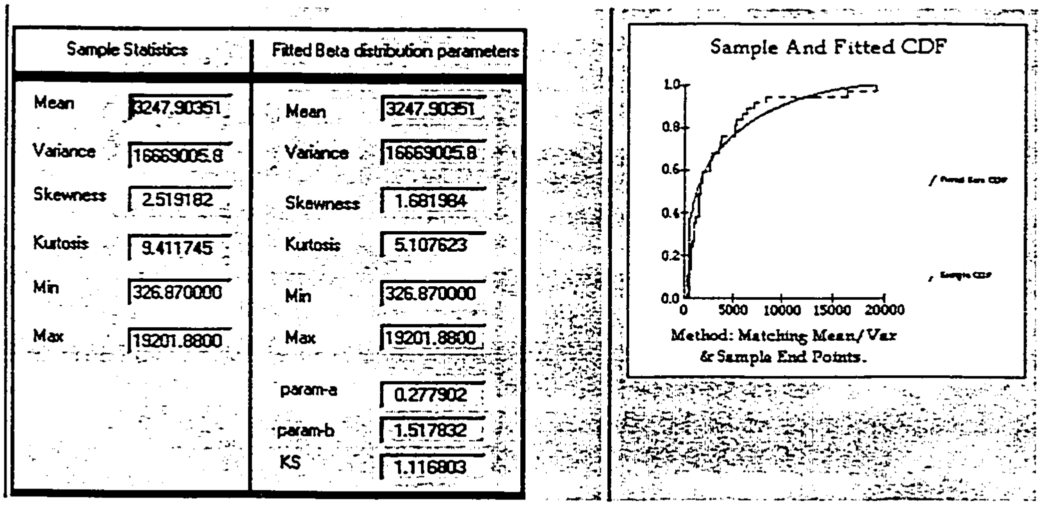
In order to gain a better understanding of the characteristics of the sewer rehabilitation expenditures, an analysis of different aspects of the historical costs was performed. The frequency of annual emergencies and how pipe class attributes are related to these occurrences was also analysed.

The rehabilitation construction projects were separated in to two groups, normal costs and the emergency costs per lineal metre. The historical data ranged from 1991 to 1998 and the costs were calculated into present worth. The software program 'BETAFIT' of the Construction Engineering and Management department, University of Alberta was used to find out what distribution best fit the normal and emergency historical costs most appropriately. Figures 5-2 and 5-3 illustrate the output of the program.



Sample Statistics		Fitted Beta distribution parameters	
Mean	2092.87500	Mean	2092.87500
Variance	5149266.57	Variance	5149266.57
Skewness	1.322483	Skewness	1.284589
Kurtosis	3.744339	Kurtosis	3.709149
Min	162.760000	Min	162.760000
Max	9559.78000	Max	9559.78000
		param-a	0.369476
		param-b	1.429366
		KS	0.817017

FIGURE 5-2 **Normal Cost and Fitted Beta Distributions**



Sample Statistics		Fitted Beta distribution parameters	
Mean	3247.90351	Mean	3247.90351
Variance	16669005.8	Variance	16669005.8
Skewness	2.519182	Skewness	1.681984
Kurtosis	9.411745	Kurtosis	5.107623
Min	326.870000	Min	326.870000
Max	19201.8800	Max	19201.8800
		param-a	0.277902
		param-b	1.517832
		KS	1.116803

FIGURE 5-3 **Emergency Cost and Fitted Beta Distributions**

Both the normal and emergency cost distributions were plotted using a cumulative density function. In both cases the best method to fit the actual data to the theoretical beta distribution was the method of matching mean/variance and sample end points. The comparative statistics between the two distributions are shown in Table 5-6.

TABLE 5-6 **Comparative Statistics, Normal and Emergency Beta Distributions**

	Normal	Emergency
Mean	2,092.88	3,247.90
Variance	5,149,266.57	16,669,005.80
Skewness	1.28	1.68
Kurtosis	3.71	5.11
Min	162.76	326.87
Max	9,559.78	19,201.89
param-a	0.3695	0.2779
param-b	1.4294	1.5178
KS	0.8170	1.1168

By comparing the statistics between the normal and emergency cost distributions, it was evident that there was a definite difference between the attributes of the two respective historical distributions. For example the mean cost of emergency projects is 55 % greater than projects that are normally scheduled. The variance of the emergency distribution is three times greater than that of the normal distribution. This suggests a wide variability in the type of work the emergency project demands, the rushed time frame and adverse working conditions that some of these emergency projects are completed in.

5.5 EMERGENCY FREQUENCY ANALYSIS

The emergencies throughout the historical data were accounted for different attributes of each project. The objective was to analyse the data to determine if there are any trends that stand out that would not be expected. The frequency of emergency occurrences of each particular pipe characteristic was totalled and a percentage from the total emergencies in that characteristic was calculated. This percentage was compared against the actual total length of pipe containing this characteristic in the entire local sewer infrastructure system.

The ideal infrastructure system would have no emergencies. This would mean the pipe system would be perfectly structurally intact and construction crews would never have to be called at odd hours of the day and work in extraneous circumstances driving the cost of repair up higher than a normal planned repair. Unfortunately this is not how real infrastructure systems behave and structural fatigue, material deterioration and ground movements must be expected.

A methodology was needed to determine what should be considered normal and what is critical behaviour when analysing the frequencies of emergencies in a system. The following approach was taken. If the percentage frequency of emergencies of a particular characteristic of a pipe infrastructure system is less than the total distribution percentage of the same characteristic of the entire infrastructure system, then this behaviour should be considered normal. If the percentage frequency of emergencies of a particular characteristic of a pipe infrastructure system is greater than the total distribution percentage of the entire infrastructure system, then this behaviour should be considered critical. If the behaviour was critical, then special attention should be warranted to this particular pipe characteristic of the local sewer infrastructure system. The following nomenclature illustrates this.

Normal Emergency Behaviour:

$$\%_{\text{Emergency}} < \%_{\text{System}}$$

Critical Emergency Behaviour:

$$\%_{\text{Emergency}} > \%_{\text{System}}$$

Where:

$\%_{\text{Emergency}}$ = Percentage frequency of emergencies for a particular sewer infrastructure characteristic.

$\%_{\text{System}}$ = Percentage total distribution of a particular sewer infrastructure characteristic.

The three characteristics that were compared were pipe age, pipe size, and waste type as shown in the following Figures 5-4, 5-5, and 5-6.

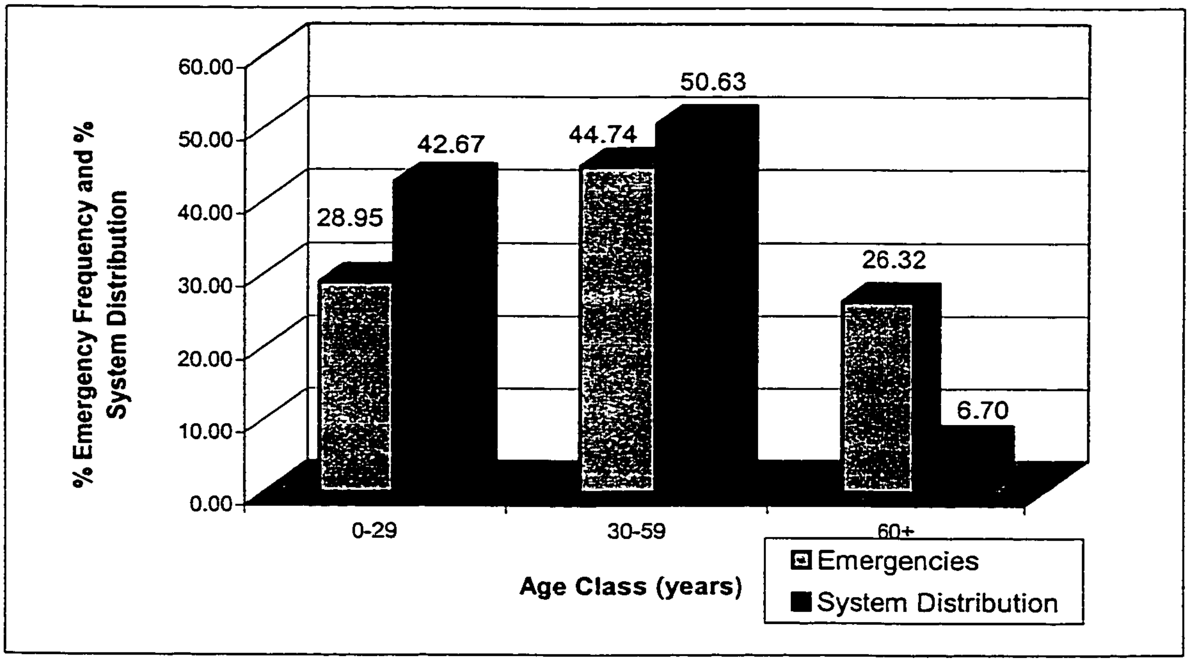


FIGURE 5-4 Age Class Emergency Frequencies vs. System Distribution

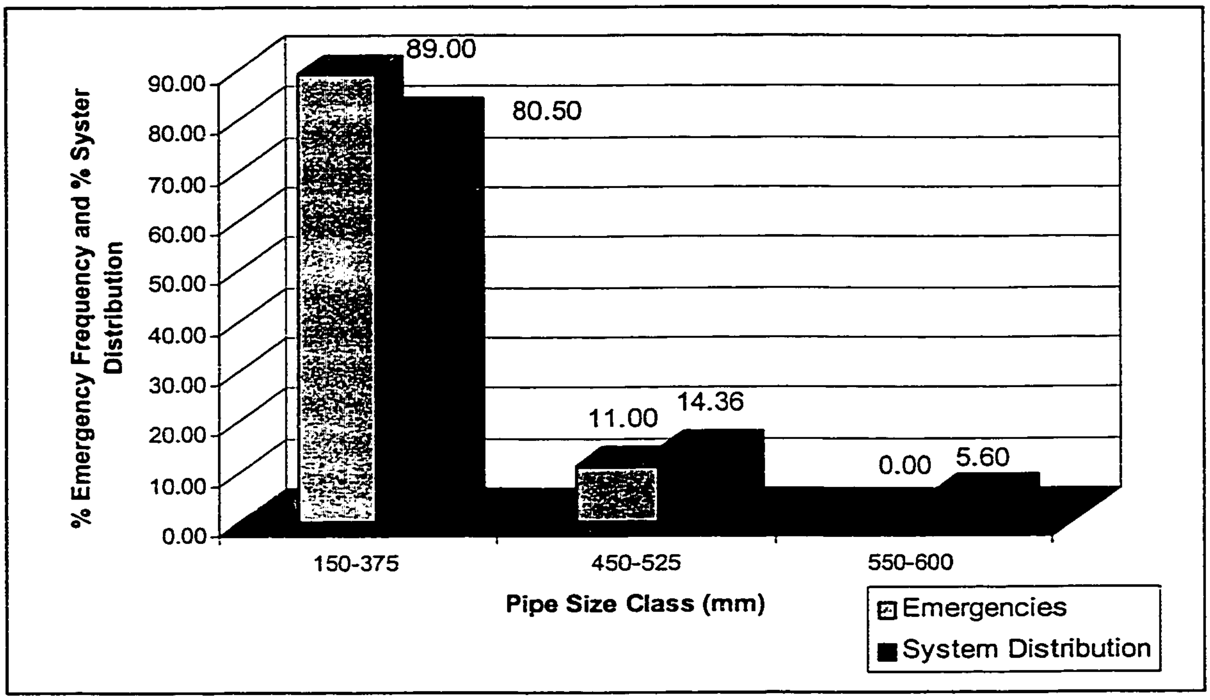


FIGURE 5-5 Pipe Size Class Emergency Frequencies vs. System Distribution

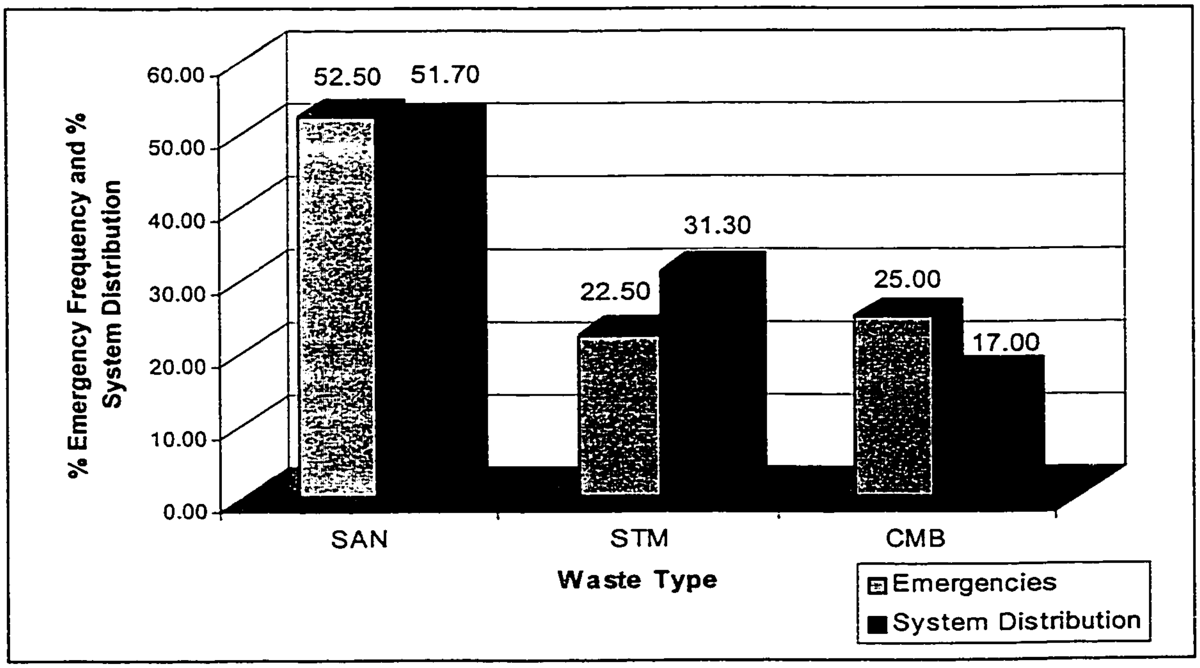


FIGURE 5-6 Waste Type Emergency Frequencies vs. System Distribution

The comparison of the pipe age, pipe size, and waste type characteristics yielded a calculation of the difference in percentage emergency frequency to percentage total system distribution, in Table 5-7.

TABLE 5-7 Comparison of Emergency to System Distribution Values

System Characteristic				Critical % Difference
Age				
0-29	$\%_{\text{Emergency}}$	<	$\%_{\text{System}}$	
30-59	$\%_{\text{Emergency}}$	<	$\%_{\text{System}}$	
60+	$\%_{\text{Emergency}}$	>	$\%_{\text{System}}$	19.62
Size				
150-375	$\%_{\text{Emergency}}$	>	$\%_{\text{System}}$	8.50
450-525	$\%_{\text{Emergency}}$	<	$\%_{\text{System}}$	
550-600	$\%_{\text{Emergency}}$	<	$\%_{\text{System}}$	
Waste				
SAN	$\%_{\text{Emergency}}$	>	$\%_{\text{System}}$	0.80
STM	$\%_{\text{Emergency}}$	<	$\%_{\text{System}}$	
CMB	$\%_{\text{Emergency}}$	>	$\%_{\text{System}}$	8.00

There were four incidents where the emergency frequencies were greater than the actual system distribution. The most critical category was the age class greater than 60 years old. This finding is of considerable importance because it quantitatively shows that sewer pipes with an age of greater than 60 years are more susceptible to structural breakdown, causing damage that warrants emergency construction work. The pipe size category of 150-375 mm and the CMB waste type were of a small difference that should receive some consideration. The SAN waste type difference was of nominal value and its emergency frequency should be considered that of following normal behaviour.

When values border near both the normal emergency and critical emergency behaviour, it is debatable whether the behaviour is critical or not. This 'degree of criticality' is an avenue where further research could be explored. This research intended to make good use of the pipe classes that were developed. A more comprehensive, detailed study of individual sewer pipe characteristics would be of considerable value. This proposed study would contribute to the understanding of sewer emergency behaviour and compliment this research.

5.6 LOCATION PRIORITIZATION

Sewer pipes were grouped into pipe classes that were made up of five common characteristics. An extensive analysis was performed on the local sewer infrastructure database in order to calculate the total length of pipe of each pipe class in each respective cadastral in the city. Based on the length of each pipe class and their respective probability deficiencies, a normalised location prioritization number was calculated for each cadastral. The location prioritization number was utilised to rank each cadastral in priority order of rehabilitation planning. The location prioritization number was calculated using the following formula:

$$LPN_c = \lambda_1 \cdot TL_1 + \lambda_2 \cdot TL_2 + \lambda_3 \cdot TL_3 + \longrightarrow \qquad + \lambda_{89} \cdot TL_{89}$$

Where:

LPN_c = Location prioritization number for a specific cadastral.

λ_1 = Deficiency probability for a pipe class one.

TL_1 = Total length for pipe class one in each respective cadastral.

Table 5-8 shows the ranking of each cadastral using the location prioritization number.

TABLE 5-8 Cadastral Location Prioritization

Cadastral	Location Prioritization Number	Rank
934+32	62,475.47	1
925+40	56,216.53	2
937+32	54,000.96	3
931+28	51,674.95	4
925+36	51,179.54	5
937+40	46,362.42	6
934+28	43,423.70	7
937+36	41,101.76	8
928+36	40,870.24	9
934+36	39,899.76	10
934+40	39,702.41	11
928+32	39,179.90	12
925+32	39,127.52	13
931+32	39,090.67	14
928+28	35,995.41	15
940+36	35,596.30	16
940+32	34,334.47	17
940+40	31,053.08	18
943+36	29,501.85	19
931+36	28,959.80	20
922+36	19,579.04	21
928+40	18,775.62	22
940+44	17,235.33	23
931+24	16,507.89	24
931+40	15,974.95	25
928+24	14,361.78	26
937+44	13,285.22	27
943+32	10,843.28	28
925+28	10,329.06	29
937+28	9,907.06	30
922+32	5,284.00	31
934+44	4,307.89	32
925+44	3,695.93	33
925+24	2,469.39	34
922+40	1,715.59	35
928+44	628.27	36
943+40	424.27	37

The location prioritization number is the summation of the products of each pipe class deficiency probability and total length for each separate cadastral. It is designed to differentiate in order of importance cadastrals with similar total lengths. Cadastrals with much less sewer infrastructure will inevitably be ranked at the bottom end of the scale by using the formulation of the location prioritization number. This result is reasonable since the cadastrals with the least sewer infrastructure are generally on the outskirts of the city and contain the youngest infrastructure, hence should generally be in the best condition.

5.7 CONCLUSION

A sensitivity analysis was conducted to determine if the 'Pipe Importance Factor' was an appropriate quantitative measure to use when differentiating between pipe classes with the same deficiency probability. It was determined that the pipe importance factor weights did not change the order of different pipe class deficiency probability ranking but the weights must be chosen with sound reasoning because it will change the order of classes with the same deficiency probability.

The financial planning models determined that it would require a substantial capital investment to rehabilitate all the probable deficient pipe lengths. This capital is likely much more than can be expected and therefore a more realistic model was generated using forecasted annual budgets. If the realistic model is constantly updated then a more dynamic model can be constructed with more accurate rehabilitation planning goals.

The cost analysis proved the emergency rehabilitation costs are greater than the normal rehabilitation construction costs. Certain attributes of the sewer pipe should be accounted for in some aspect of the planning process because the frequency of the emergencies was greater than its corresponding distribution in the system. These attributes were pipes greater than 60 years of age, pipe sizes in the 150-300 mm size range, and combined and sanitary waste types.

A location prioritization analysis was conducted for each of the 37 cadastrals in the City of Edmonton. The cadastrals were ranked in order of priority according to how much probable deficient length of pipe each cadastral contained. The location prioritization rankings were not used in the linear program configuration but the information from the priority rankings may be of considerable use in future planning stages.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

This thesis presented an optimization methodology for rehabilitative construction financial planning for sewer pipe infrastructure. The approach taken considered a large body of data which described the local sewer infrastructure system and broke it up into more manageable common characteristic sections, called pipe classes. The principle attribute each pipe class contained was a numerical probability that the pipe class was currently in a deficient physical state. This deficiency probability ranked the different pipe classes against each other in order of priority importance. Numerical weights were given to the pipe size and waste type pipe characteristics to help differentiate the order of pipe class priority ranking for rehabilitation.

The mathematical optimization tool used in this thesis was linear programming. Linear programming proved to be an effective method of financially planning a rehabilitative sewer infrastructure program based on priority ranked objectives and constrained resources. The objective in the model was to minimise the capital expenditure over a 20 year program period, while utilising the full annual budgets and allocating rehabilitation investment to the most important pipe classes first. The optimization and planning methodology developed in this thesis can be effectively used for other forms of rehabilitation infrastructure management planning. The infrastructure type in question could be broken up into its own unique categories, a failure probability study conducted, proper linear mathematical structure developed, and bounded by the applicable resource constraints.

The output of the model represents the optimum mathematical rehabilitation planning for each pipe class in each year. The exact nature of the numerical planned rehabilitation of each pipe class does not mean that it has not been expected that political and unpredictable circumstances will change the actual rehabilitation performed each year. The actual rehabilitation work simply has to be recorded and the numerical results inputted back into the model to revise the output over the planning period. At the least, the optimization results can be used as a guide to illustrate how the capital expenditure over the program period can be minimised and a reminder of which pipe characteristics the planning engineer should be concerned with. The optimization model can be made more realistic and accepted over time, if ongoing studies of pipe deficiency probabilities, unit rate rehabilitation costs, rehabilitation work completed to date, and forecasted annual budgets are maintained and inputted into the model.

The analysis of the historical rehabilitation costs concluded that the distribution of emergency rehabilitation construction costs is indeed greater than that of normal planned rehabilitation construction projects. This was an important determination in this research as a compelling argument for proactive planning.

The investment into a proactive research program that attempts to maximise the life span of a sewer infrastructure system while responsibly replacing deficient pipe sections prior to an emergency system failure, can only be a successful approach to take for the future. Although a proactive sewer investment research program requires current financial support from the taxpayer, the future results inevitably will offer enhanced system reliability than a practice of rehabilitation purely based on emergency response. With time, a strategic proactive plan will become more efficient if the right degree of sustained effort is committed to the program. This proactive infrastructure program should identify and eliminate more of the very sewer pipe sections that have the potential to require emergency rehabilitation response. Financially, a reduction in the amount of emergencies over time will decrease the commitment to this kind of expenditure and therefore provide greater budgetary scope for planned proactive rehabilitation.

The objectives of this research were met by analysing the City of Edmonton sewer infrastructure data and determining the extent and distributions of unique pipe classes that are present. The project rehabilitation cost data was analysed with interesting results determined with emergency project data. Together the infrastructure and rehabilitation cost data were built into a linear programming model that successfully planned rehabilitation to pipe classes in order of priority over a planning period based on the limits of the constraints. An algorithm was developed for intended implementation within an interactive computer program for city practitioners to utilise.

It will take commitment, effort and continued refinement of the proactive strategy to produce a successful long-term program. If a methodology used is one of neglect and rehabilitation based on emergency response, then the infrastructure system will continue to age and deteriorate at a combined rate that may prove more detrimental than expected. The end result could be very damaging to the community and the cost to fix the effect could be more than the most fortunate annual budget could hope to achieve; as many infrastructure problems throughout the world have demonstrated.

6.2 RECOMMENDATIONS FOR FUTURE WORK

The recommended further work is the development of a functional database and optimization program that is linked together. The program will be a software tool of the result of this thesis. Further development of this optimization approach would be the integration of other factors related to the placement of each sewer pipe and make use of more data to develop a much more comprehensive model.

6.2.1 Software Development

The software developed will contain the large amount of local sewer system data in a database platform such as Access. User interfaces developed using Visual Basic will allow the user to input data, edit data, and adjust the variables that make up the optimization model. A separate piece of optimization software will be linked to the program and configured using the algorithm in this thesis. The advantage of using this dynamic computer program is that the variables such as the average unit rate of rehabilitation cost per metre, annual budgets, deficiency probabilities and actual deficient pipe length can be updated in the program when more accurate figures become available.

The preliminary name for this piece of software is PRISM, which stands for "Proactive Rehabilitative Infrastructure Sewer Management". Figure 6-1 illustrates the relational structure of the computer software.

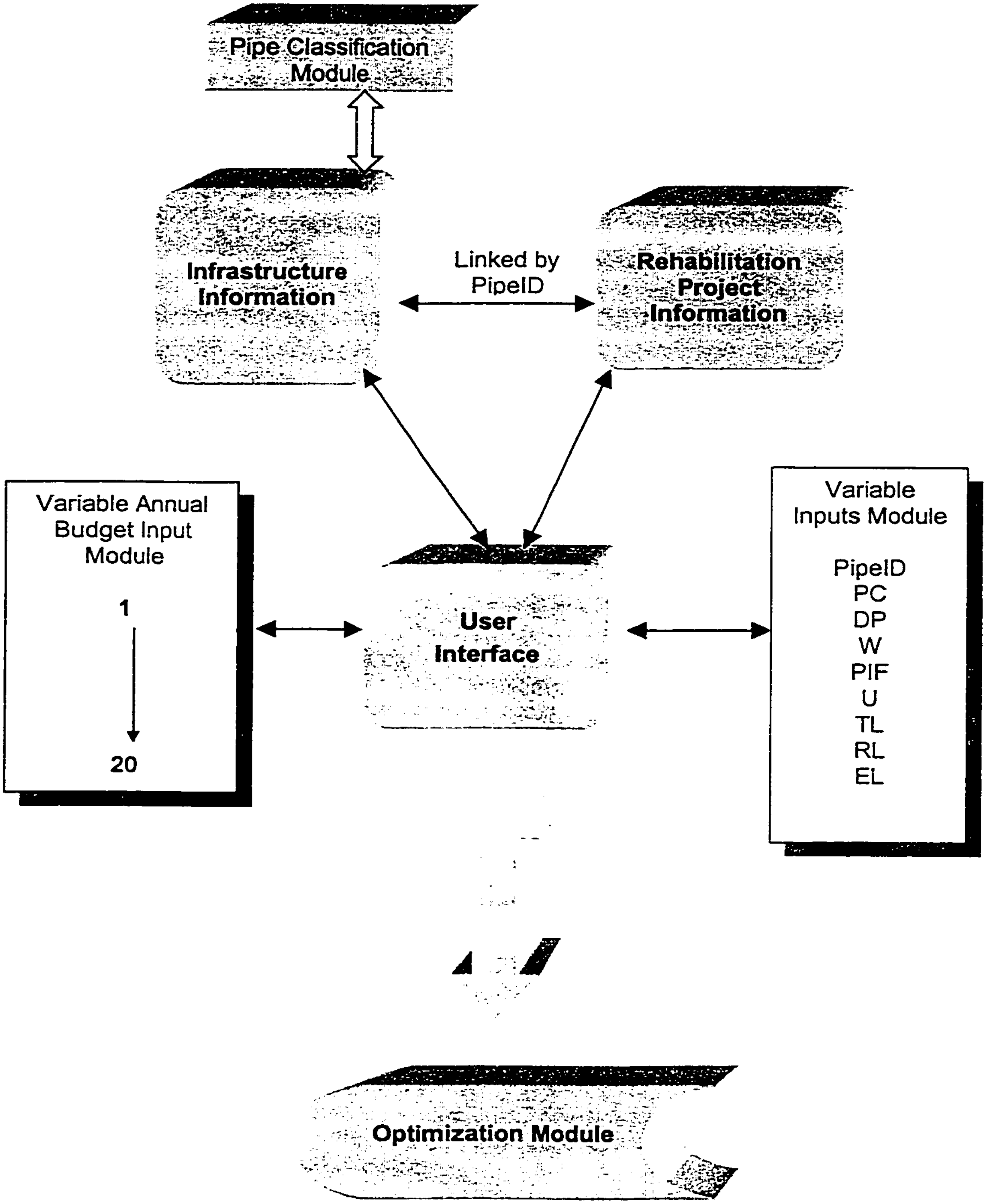


FIGURE 6-1 Relational Structure of PRISM

Where:

PC = Pipe Class

DP = Deficiency Probability

W = Pipe importance factor weights

PIF = Pipe Importance Factor

U = Average rehabilitation unit cost per metre

TL = Total length of pipe

RL = Rehabilitated length of pipe

EL = Effective deficient length of pipe

The Infrastructure Information and the Rehabilitation Project Information tables will contain the main database information as shown in Tables 3-9 and 3-10 in Chapter 3. The Pipe Classification Module is code that reads each pipe section record and inputs the appropriate pipe class number to it based on its characteristics. The Variable Input Module allows the user to update or edit the deficiency probability, the pipe importance factor weights, and the unit rehabilitation rate. It also calculates the current length of pipe for each pipe class that is probably deficient by allowing an input field for the user to add the length of each section of pipe that is deficient after the inspection is completed. This is done by subtracting rehabilitative work performed on the particular pipe section from its total length. This new adjusted length is multiplied by the deficiency probability to get the new effective length. The overriding factor is that if an inspection has been performed on that pipe section, then the amount of deficient pipe determined by the inspection takes precedence as the new effective length. The following equation show this.

$$EL = (TL - RL) \cdot DP$$

OR

EL from inspection

The Variable Annual Budget Input Module allows the user to adjust any annual budget in the program period once these forecasts become more accurate. Each time the user requires a new optimized rehabilitation plan they activate the Optimization Module. The new effective lengths are then calculated for each pipe class and the adjusted variables are inputted into the optimization module, calculating an updated financial rehabilitation plan and keeping the work performed in the previous years constant.

Reporting modules will be constructed that can be generated for various portions of the data that are desirable. The final computer package should be a useful tool if used effectively to maintain more accurate data and forecast future work.

6.2.2 Expanded Model

An expanded model where not only the physical makeup of the sewer pipe is considered but also the surrounding influences of its placement, is the potential next step in the evolution of this sewer infrastructure optimization strategy. The placement of each sewer pipe section could be weighted upon what negative influence the pipe would have if it broke or backed up. For example, the placement of each pipe section could be weighted from high priority to low if the pipe section was placed under a highway, arterial, or local collector respectively. Many other factors could be included in this priority placement strategy such as sewer pipes in dense urban areas and sewer pipes within close proximity to ground slopes of sensitive stability. The location prioritization number could be utilised in this model frame to optimize rehabilitation by cadastral.

In order to incorporate all of these location factors in this expanded model, an extensive data collection program would have to be performed. The location data will likely have to be derived from as built drawings and subsections of cadastral maps. It is unlikely that the data will be collected from automated Autocad files in the most desired tabular format. An extensive manual comparative analysis would need to be performed to input the proper pre-defined location factors for each section of sewer pipe for each kind of location category. The completion of this analysis would be detailed and time intensive, but the collection of the data would be invaluable.

The data in the model could be further broken up and more collectively grouped to provide different options of analysis and optimization. For example the optimization model could be run where inspection and then rehabilitation is first applied to the most deficient pipe classes that are near hospitals and major intersections. This extended model has many possibilities and with dedicated application and refinement the model could develop into an invaluable tool.

CHAPTER 7

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APPENDIX A

TOTAL PIPE CLASS & CADASTRAL TABULATION

	Pipe Class													
Cadastral	1	2	3	4	5	6	7	8	9	10	11	12	13	14
922+32							3931.74	340.19	1093.55					977.55
922+36							705.38	3329.40	3606.89					3794.92
922+40														281.32
925+24														1058.52
925+28							2979.11							2886.08
925+32	9167.12	19449.03					2288.61	2903.77	7289.64	859.98	13768.42			4508.71
925+36	5310.80	893.94					70.01	10431.64	9620.92	18168.96	3110.90			1616.97
925+40							8310.71	15596.28	2088.04	19332.12				8404.94
925+44														1266.66
928+24							1112.24	4005.02	300.53					8212.04
928+28	5048.10	79.71	6059.46				5917.40	6932.88	2267.29	7989.92	1863.23	233.36		9184.41
928+32	6737.07	15621.22	11343.22	82.30		4611.51	1095.02	207.95		2912.87	18995.25	1764.13	6884.04	201.47
928+36	535.08	2242.95	3191.25	151.20	6130.54	7780.50	183.50	788.40	1782.67	1116.60	4738.29	3381.01	8576.15	704.91
928+40	2792.56	1320.77	945.63	488.26	5827.85		167.02	2764.45	931.88	3014.14	602.40	5056.79		369.69
928+44							110.64		277.65					
931+24							4551.56		7675.90	226.62				7067.97
931+28	3598.95	10831.29	12925.16	14930.93	3280.64	515.3	2186.04	723.48	1963.07	9204.07	8907.88	8000.83		3346.53
931+32	748.13	747.29	6450.44	8685.27	9753.64	12820.81	118.87				1916.18	16025.05	11426.87	333.56
931+36			98.76		84.73	343.25		160.16		5.10	293.96	314.20	1101.69	432.97
931+40	1706.63	77.71		76.65	1118.73		250.67	2816.76	2767.73	610.65	50.29	902.42		174.79
934+28	1334.93	3547.50	1540.77	10907.24	6384.38	4768.54	3438.84	7956.29	2752.78	532.63	3342.23	10288.96	594.37	1222.15
934+32		294.29	360.57	1179.77	1154.88	15275.62	47.24				945.05	2744.68	26484.46	1200.37
934+36		64.01			208.49	61.26			33.53		414.25	212.77	3107.92	295.04
934+40	114.89		698.00	15486.35	9186.02	4411.75	62.18	60.96	359.41	55.78	369.69	18954.09	657.60	343.35
934+44	2634.54	2298.04						12.50		45.92	3218.53			
937+28	596.03	401.72	156.36		704.00		159.71	1765.13	1824.62	203.61	430.68			749.17
937+32	3023.14	1225.26	4445.65	2188.15	8093.19	19307.20	76.50	114.60	69.34	935.74	1450.39	6278.70	23325.77	1876.46
937+36		1365.20	4607.23	9255.81	2316.82	331.35			19.66	33.22	2430.20	7539.51		2904.83
937+40	695.09	2810.56	1971.45	768.09	810.15	22597.43	835.60	208.63	4390.07	2021.23	3148.16	3019.38	2310.48	1556.05
937+44	585.67	788.04				1158.53	936.75	6231.16	1753.08	1049.02	382.55			1605.07
940+32		3199.41	6237.74	9808.97	33.53	82.50	3086.28	4349.38	5265.44	11144.40	1202.37	8137.48		631.74
940+36	18602.83	10942.92	11946.16	106.68			5568.09	68.88	185.02	10936.29	5882.55	317.61		929.11
940+40	16122.53	15388.14	2191.65	346.57	413.68		2597.40	302.82	5536.65	4422.80	5494.72	254.17		1764.68
940+44							10274.28	8204.95	2553.46					569.48
943+32				30.18			4718.65	3521.75	4657.92					3596.88
943+36							19766.23	10578.95	9503.82					1308.77
943+40														
Total (m)	79,354.09	93,589.00	75,169.50	74,492.42	55,501.27	94,065.55	85,546.47	94,376.38	80,570.56	94,821.67	82,958.17	93,425.14	84,469.35	75,377.16

Cadastral	15	16	17	18	19	20	21	22	23	24	25	26	27	28
922+32	179.65						32.61			566.53	307.92	641.44	805.25	
922+36	2197.00					3397.16	3022.16			3731.07	2189.81	1927.79	2378.36	
922+40										379.02		426.70		
925+24						5223.60				192.21		1170.89		
925+28						2083.46	7282.87			2986.30	189.89	393.32	954.17	
925+32	4558.91			138.38		4827.65	48.70	35.36	4372.69	2704.64	3109.97	2371.63	1480.63	
925+36	14726.54			272.19		1516.35	1994.45		503.05	9075.34	11031.12	3528.05	5849.12	181.36
925+40	15400.55					6.10	5052.09			11688.03	7980.52	2503.25	4869.60	
925+44						123.50	3632.34			570.31		283.98	417.70	
928+24	419.09					10250.87	3804.03			2082.59	287.73	3482.74	1254.45	
928+28	6463.36					5790.90	1371.13		1107.44	4089.15	5267.26	5707.21	3139.65	
928+32	2200.33			677.84	3393.31			1718.74	6549.18	831.04	1039.15	456.95	619.09	144.01
928+36	2427.81	3540.35	1414.71	2273.08	12554.97		16.00	15883.54	3618.89	1311.54	398.59	1479.81	1093.74	2130.77
928+40	701.93					99.80			960.46	2975.96	750.71	1289.12	3002.22	
928+44						582.70	68.00			84.90		101.80	251.10	
931+24	4089.56					6159.71	2557.01			1848.03	225.76	2094.88	1324.92	
931+28	5333.36					3224.03	981.60		4643.55	2180.25	1913.76	2929.59	2495.49	
931+32	193.85	409.69	164.89	292.61	3586.93	327.05		1299.18	6685.65		53.34			55.47
931+36	1859.65	13145.66	8424.34	1173.28	8441.51	140.18		5470.23	1225.39	669.79		392.01	273.55	1624.84
931+40	496.33			6033.78	2822.85			6106.41	525.45	68.28	2078.07	309.21	288.78	1448.83
934+28	2137.73				16.15	3241.97	480.06		4202.16	1802.57	2436.59	2763.64	873.03	
934+32	2260.65	10594.41	14486.49	1117.88	13612.44		295.20	11699.20	8228.74	922.19		1272.79	580.34	698.38
934+36	705.48	3966.79	30240.30	1104.31	6184.98			5820.66	436.79	306.42	111.10	430.91	179.22	1558.82
934+40	256.49	2810.44	268.98	13234.92	2975.82		384.04	7462.17	5534.44			601.84	124.97	1770.00
934+44				140.06			136.86	203.54	682.27					
937+28				62.48		35.06	1004.61	70.10		899.11	2174.49	1115.74	2560.78	
937+32	1122.58	7413.19		3795.20	7754.29	658.38	49.23	3267.76	8632.98	494.45		834.27	797.14	282.70
937+36	767.79	12421.64	10209.52	4797.94	8999.37			3718.50	4900.78	1082.22		1668.13	746.25	2718.33
937+40	465.75	11592.16	136.86	3176.11	6725.83	2404.19	628.94	10570.40	2717.94	1468.43	856.96	2505.91	907.97	1184.54
937+44	4699.34						206.04		163.52	882.08	1988.06	1665.25	835.06	
940+32	2548.94			239.27	108.30	5110.90	108.21		2746.66	1652.11		1771.63	1341.09	
940+36	2939.33	143.04		120.55	156.76	2237.93	2470.58		2725.48	735.80	998.38	714.25	710.22	143.71
940+40	1174.83			73.46		5314.80	652.55		781.36	799.61	1801.09	1542.75	548.09	
940+44	1539.30						136.00			298.29	3158.16	370.56	218.17	
943+32	482.18					2422.94				1479.21		1542.12	1031.58	
943+36	1540.20					2459.94	1694.94			163.34	839.78	539.81	1323.31	
943+40	466.66					737.08						36.24		
Total (m)	84,355.17	66,037.37	65,346.09	38,723.34	77,333.51	68,376.25	38,110.25	73,325.79	71,944.87	61,020.81	51,188.21	50,866.21	43,275.04	13,941.76

Cadastral	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
922+32	8.50																
922+36	1835.48						332.40										
922+40																	
925+24							349.88										
925+28	291.40																
925+32	179.70						421.69		17.37								
925+36	2854.96						118.87	117.38							4.14		
925+40	2606.73						70.41										
925+44	177.33						63.10										
928+24							474.79										
928+28	377.65						483.85										
928+32	224.94		109.72						76.71								
928+36		1004.16	1355.07	105.31	306.27		171.44	344.12	682.91	64.92							
928+40	1608.88																
928+44																	
931+24							218.50										
931+28							259.92										
931+32		158.85		215.64					193.25								
931+36		824.67	1033.77	448.67	937.74	1762.62	14.78	1382.15	59.90	385.41	112.93		6.09	110.55	154.82		103.78
931+40	233.17	464.54	731.55		979.16		31.39	960.56									
934+28							1134.70										
934+32		1686.82	1126.48	954.57	1348.50	913.25		437.35	690.98					71.32			
934+36		742.50	1154.54	3947.78	926.47	2279.18		816.70	604.23	99.36	812.91	643.22	84.43		116.31	123.23	90.07
934+40		1653.11	1037.44	52.20	1335.39			21.64	277.53	46.02		3.51			16.52		
934+44																	
937+28	1174.51						332.84										
937+32		1688.86	434.95	495.29	1182.39	460.04	90.98	295.66	291.85	1406.55		99.36	490.41				
937+36		1751.95	503.71	1256.23		567.69	338.62	146.00	12.19	969.93	31.67		75.28			105.50	
937+40	373.22	1664.75	60.50	364.07		611.53	1065.62	81.73	560.84	252.84	404.63			126.18			
937+44	3.19						76.20		61.26								
940+32									37.49								
940+36			142.34				96.32						73.46				
940+40			59.74				99.73		23.16								
940+44	88.00																
943+32																	
943+36							73.10										
943+40																	
Total (m)	12,037.66	11,640.21	7,749.81	7,839.76	7,015.92	6,594.31	6,319.13	4,603.20	3,589.67	3,225.03	1,362.14	746.09	729.67	308.05	291.79	228.73	193.85

Cadastral	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61
922+32	1629.89		124.26				1226.49	174.90								
922+36	974.53	7911.70	5160.74			53.34	4424.91	775.44			160.93				43.58	313.43
922+40							4170.92									
925+24																
925+28	145.75	3349.29	1591.40				2764.54	118.92								
925+32	1539.79	635.12	1431.84	2728.99	1628.31	2263.74	1641.33	2138.71				2597.34				206.00
925+36	1149.99	6048.51	3388.87	794.44	319.45	186.84	3382.91	966.66		62.20		683.34			14.93	537.50
925+40	1819.60	8595.60	6721.26				8334.43	609.60								622.99
925+44		424.71	1790.30				1101.90	982.85								300.91
928+24	228.20	1786.76	3001.32				270.96									253.85
928+28	1177.69	512.85	4851.55	104.55		762.47	1155.37					1324.15			1780.74	
928+32		231.55	408.58	3985.64	858.76	4546.51	138.12					3246.60	1.50		62.17	334.16
928+36	46.63	845.35	1166.00	1322.62	2766.57	2256.05	963.64		50.23	317.77		2273.76	328.94	238.43	56.59	75.13
928+40	2178.13	6250.57	1003.99	1527.97	992.75	48.76	1934.44	519.90				825.50			458.50	217.24
928+44		49.00	101.80				154.61									
931+24	54.71	1663.12	1269.96				530.17									
931+28	1882.32	983.10	3683.46	24378.08	1034.89	3490.97	296.23	209.78	89.91			1998.27			185.93	174.16
931+32	4.70			4865.64	2749.26	3185.40	10.00	740.51		229.11	2999.74	2276.96	2.13	54.25	29.87	
931+36						418.92	174.19		889.33	1746.55	73.46	150.10	1474.80	1358.89	23.85	
931+40	308.87		580.19	202.68	542.21	503.45	65.37	20.42		318.56		51.51	515.19	313.75	329.65	
934+28	4968.05	4158.55	2258.93	17239.90	146.30	2122.06	600.35	2660.51	421.24			1967.04				271.94
934+32	83.21			3700.88	4163.57	1979.91	39.02		50.90	558.55	1654.41	2369.98	134.58	707.56	349.16	212.24
934+36	9.14				85.95	962.71	287.07			1892.76	85.16	439.21	1052.72	304.95	308.46	75.59
934+40		31.63		1135.83	460.55	2743.48	135.64			243.02		6394.97	411.43	2.75	144.02	
934+44				393.33		764.88	10.54					725.28			45.50	
937+28	1774.23	4528.65	1754.23	13.41	854.80		136.49	940.92								
937+32	715.06	97.50	128.00	1606.59	5914.56	4572.16	153.22	167.94	4441.71	842.83	534.62	3920.16	425.20	158.49	394.64	271.28
937+36		51.51		1262.48	101.80	1952.70	1051.04			1807.74	22.71	606.56	853.97	571.98	184.71	
937+40	717.50	4438.92	2567.91	4448.92	771.33	2332.39	1240.60			466.98	817.39	587.66	110.03	141.28		102.57
937+44	6.27	373.32	1112.78	369.42	3269.98	221.43	99.37					298.09				295.36
940+32	4703.67	117.82	1823.51	406.33	3465.94	1624.37	23.00		352.50			2281.31			73.76	
940+36	1091.76	458.50	923.33	2621.23	7429.46	878.90	107.09		958.44			1050.61			17.07	
940+40	1460.71	668.39	1829.24	791.09	7210.67	460.15	22.97	354.48	1961.53		102.11	581.56				75.90
940+44	208.78	2904.32	807.90					597.71								114.00
943+32	143.68	647.14	80.25													
943+36	2943.76	322.78	699.73		2927.44		39.63	199.85								
943+40																
Total (m)	31,966.62	58,086.26	50,261.33	73,900.02	47,694.55	38,331.59	36,686.56	12,179.10	9,215.79	8,486.07	6,450.53	36,649.96	5,310.49	3,852.33	4,503.13	4,454.25

Cadastral	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79
922+32														213.87				
922+36					191.71	88.39											7.32	
922+40																		
925+24																		
925+28					4.88									508.22			415.44	
925+32					236.73								672.45	1088.47				
925+36					331.92												88.00	
925+40					611.70													
925+44																		
928+24																		
928+28					262.97									343.63				
928+32				33.53	21.34			129.53					448.36	385.66				
928+36	15.85			28.35				68.39										
928+40																		
928+44																		
931+24					41.60									41.50			23.79	
931+28					65.53													
931+32				13.75		104.02					267.61	98.54	1670.18		106.07			
931+36	297.94	818.53	73.15			328.62	222.81	352.61	23.77	197.13			407.76	379.04		329.64		
931+40	247.77			84.95				370.58										
934+28																	5.50	
934+32	1372.12	1461.02	2396.10		205.54	335.57	619.09	3.66										
934+36	741.73	914.75	233.80	135.96	6.40	1714.70	843.99	409.24	393.81	84.50				22.86		27.87	24.95	148.13
934+40	105.98	108.51	74.67	787.29			143.26	386.94						1324.71	778.30	139.17		3.50
934+44													430.83				3.35	
937+28					99.00													
937+32	630.02	53.34	627.28	614.01	288.00	121.92	308.15	13.72					3.20	4.50		149.39	7.50	292.14
937+36	199.79	226.17	90.87	355.86	39.50			615.82									22.50	
937+40	828.90			2002.52			293.28							120.40	102.72			
937+44					295.05									445.35			24.69	
940+32														169.83				
940+36														456.90				
940+40					100.00													
940+44																		
943+32														6.00				
943+36														132.00				
943+40																		
Total (m)	4,440.10	3,582.32	3,495.87	4,056.22	2,801.87	2,693.22	2,430.58	2,350.49	417.58	281.63	267.61	98.54	3,632.78	5,642.94	987.09	646.07	623.04	443.77

Cadastral	80	81	82	83	84	85	86	87	88	89	Total (m)
922+32		38.25									12,292.59
922+36						27.00					52,580.84
922+40											5,257.96
925+24											7,995.10
925+28											28,945.04
925+32											103,311.42
925+36											118,952.62
925+40											131,224.55
925+44											11,135.59
928+24											41,227.21
928+28											91,649.33
928+32											103,329.07
928+36	292.76										106,594.11
928+40											51,628.27
928+44		8.23									1,790.43
931+24											41,665.27
931+28											142,848.35
931+32	15.85	34.00								6.10	102,126.20
931+36						9.91					62,764.13
931+40											38,586.54
934+28											114,520.58
934+32	34.14		58.52								145,174.64
934+36	9.81	58.19	12.50		94.81		54.00		48.77		79,368.47
934+40		21.34						52.12			106,256.65
934+44											11,745.97
937+28											26,522.48
937+32	49.68										141,955.41
937+36											98,610.78
937+40			80.62								120,222.19
937+44											31,880.98
940+32											83,885.88
940+36											95,887.58
940+40						30.00					83,355.78
940+44											32,043.36
943+32				149.04							24,509.72
943+36											57,057.38
943+40											1,239.98
Total (m)	402.24	160.01	151.64	149.04	94.81	66.91	54.00	52.12	48.77	6.10	2,510,142.45

APPENDIX B

FINAL 89 PIPE CLASS CHARACTERISTICS

Pipe Class	Age (years)	Diameter (mm)	Material	Waste Type	Ave. Depth of Cover (m)
1	30-33	150-375	TP	SAN	0-6
2	34-37	150-375	TP	SAN	0-6
3	38-40	150-375	TP	SAN	0-6
4	41.42	150-375	TP	SAN	0-6
5	43-44	150-375	TP	SAN	0-6
6	45-59	150-375	TP	SAN	0-6
7	0-21	150-375	TP	SAN	0-6
8	22-23	150-375	TP	SAN	0-6
9	24-25	150-375	TP	SAN	0-6
10	26-29	150-375	TP	SAN	0-6
11	30-39	150-375	CP	STM	0-6
12	40-44	150-375	CP	STM	0-6
13	45-59	150-375	CP	STM	0-6
14	0-22	150-375	CP	STM	0-6
15	23-29	150-375	CP	STM	0-6
16	60-85	150-375	TP	CMB	0-6
17	86+	150-375	TP	CMB	0-6
18	30-45	150-375	TP	CMB	0-6
19	46-59	150-375	TP	CMB	0-6
20	0-15	150-375	PVC	SAN	0-6
21	16-29	150-375	PVC	SAN	0-6
22	30-59	150-375	CP	CMB	0-6
23	30-59	450-525	CP	STM	0-6
24	0-29	450-525	RCP	STM	0-6
25	0-29	150-375	TP	SAN	6+
26	0-29	450-525	CP	STM	0-6
27	0-29	550-600	RCP	STM	0-6
28	30-59	450-525	CP	CMB	0-6
29	0-29	150-375	RCP	SAN	6+
30	30-59	450-525	TP	CMB	0-6
31	30-59	450-525	RCP	CMB	0-6
32	60+	450-525	TP	CMB	0-6
33	30-59	550-600	RCP	CMB	0-6
34	60+	550-600	TP	CMB	0-6
35	0-29	550-600	CP	STM	0-6
36	0-29	150-375	TP	CMB	0-6
37	30-59	150-375	TP	STM	0-6
38	30-59	550-600	TP	CMB	0-6
39	60+	150-375	CP	CMB	0-6
40	60+	150-375	NC	CMB	0-6
41	30-59	550-600	TP	CMB	6+
42	30-59	550-600	CP	CMB	6+

Pipe Class	Age (years)	Diameter (mm)	Material	Waste Type	Ave. Depth of Cover (m)
43	0-29	150-375	TP	CMB	6+
44	60+	450-525	CP	CMB	0-6
45	0-29	450-525	TP	CMB	0-6
46	0-29	450-525	TP	SAN	0-6
46	0-29	450-525	TP	SAN	6+
46	0-29	450-525	PVC	SAN	6+
46	0-29	450-525	PVC	SAN	0-6
46	0-29	450-525	CP	SAN	0-6
46	0-29	450-525	RCP	SAN	0-6
46	0-29	450-525	RCP	SAN	6+
46	0-29	450-525	CP	SAN	6+
47	0-29	150-375	PVC	SAN	6+
47	0-29	150-375	CP	SAN	6+
47	0-29	150-375	RCP	SAN	0-6
48	0-29	150-375	CP	SAN	0-6
49	30-59	150-375	PVC	SAN	0-6
49	30-59	150-375	CP	SAN	6+
49	30-59	150-375	TP	SAN	6+
49	30-59	150-375	CP	SAN	0-6
50	30-59	450-525	RCP	SAN	6+
50	30-59	450-525	CP	SAN	0-6
50	30-59	450-525	TP	SAN	6+
50	30-59	450-525	RCP	SAN	0-6
50	30-59	450-525	CP	SAN	6+
50	30-59	450-525	TP	SAN	0-6
51	30-59	550-600	TP	STM	6+
51	30-59	550-600	TP	STM	0-6
51	30-59	550-600	CP	STM	6+
51	30-59	550-600	RCP	STM	6+
51	30-59	550-600	CP	STM	0-6
51	30-59	550-600	RCP	STM	0-6
52	0-29	150-375	PVC	STM	6+
52	0-29	150-375	RCP	STM	6+
52	0-29	150-375	TP	STM	0-6
52	0-29	150-375	TP	STM	6+
52	0-29	150-375	PVC	STM	0-6
52	0-29	150-375	CP	STM	6+
52	0-29	150-375	RCP	STM	0-6
53	0-29	550-600	PVC	SAN	6+
53	0-29	550-600	PVC	SAN	0-6
53	0-29	550-600	CP	SAN	6+
53	0-29	550-600	RCP	SAN	0-6
53	0-29	550-600	CP	SAN	0-6
53	0-29	550-600	RCP	SAN	6+
54	30-59	550-600	CP	SAN	0-6
54	30-59	550-600	CP	SAN	6+
54	30-59	550-600	RCP	SAN	6+

Pipe Class	Age (years)	Diameter (mm)	Material	Waste Type	Ave. Depth of Cover (m)
54	30-59	550-600	RCP	SAN	0-6
54	30-59	550-600	TP	SAN	6+
54	30-59	550-600	TP	SAN	0-6
55	0-29	150-375	RCP	CMB	6+
55	0-29	150-375	PVC	CMB	6+
55	0-29	150-375	CP	CMB	6+
55	0-29	150-375	PVC	CMB	0-6
55	0-29	150-375	RCP	CMB	0-6
55	0-29	150-375	CP	CMB	0-6
56	60+	150-375	CP	SAN	0-6
56	60+	150-375	TP	SAN	6+
56	60+	150-375	TP	SAN	0-6
57	30-59	450-525	TP	STM	0-6
57	30-59	450-525	RCP	STM	6+
57	30-59	450-525	CP	STM	6+
57	30-59	450-525	RCP	STM	0-6
58	0-29	450-525	TP	CMB	6+
58	0-29	450-525	RCP	CMB	6+
58	0-29	450-525	CP	CMB	6+
58	0-29	450-525	CP	CMB	0-6
58	0-29	450-525	RCP	CMB	0-6
59	30-59	150-375	RCP	CMB	0-6
59	30-59	150-375	PVC	CMB	6+
59	30-59	150-375	RCP	CMB	6+
59	30-59	150-375	CP	CMB	6+
59	30-59	150-375	TP	CMB	6+
60	30-59	150-375	TP	STM	6+
60	30-59	150-375	RCP	STM	6+
60	30-59	150-375	CP	STM	6+
60	30-59	150-375	RCP	STM	0-6
61	0-29	450-525	TP	STM	0-6
61	0-29	450-525	PVC	STM	0-6
61	0-29	450-525	CP	STM	6+
61	0-29	450-525	RCP	STM	6+
62	30-59	450-525	RCP	CMB	6+
62	30-59	450-525	TP	CMB	6+
62	30-59	450-525	CP	CMB	6+
63	60+	150-375	CP	CMB	6+
63	60+	150-375	TP	CMB	6+
64	60+	550-600	RCP	CMB	0-6
64	60+	550-600	TP	CMB	6+
65	30-59	550-600	RCP	CMB	6+
65	30-59	550-600	CP	CMB	0-6
66	0-29	550-600	CP	STM	6+
66	0-29	550-600	RCP	STM	6+
67	60+	150-375	CP	STM	6+
67	60+	150-375	TP	STM	6+

Pipe Class	Age (years)	Diameter (mm)	Material	Waste Type	Ave. Depth of Cover (m)
67	60+	150-375	CP	STM	0-6
67	60+	150-375	TP	STM	0-6
68	60+	450-525	TP	CMB	6+
69	0-29	550-600	TP	CMB	6+
69	0-29	550-600	RCP	CMB	6+
69	0-29	550-600	CP	CMB	0-6
69	0-29	550-600	RCP	CMB	0-6
70	60+	450-525	TP	STM	0-6
70	60+	450-525	CP	STM	0-6
70	60+	450-525	TP	STM	6+
71	60+	550-600	RCP	STM	0-6
71	60+	550+600	TP	STM	6+
71	60+	550-600	TP	STM	0-6
72	60+	450-525	TP	SAN	0-6
72	60+	450-525	TP	SAN	6+
73	60+	550-600	TP	SAN	6+
74	30-59	150-375	CIP	SAN	0-6
74	30-59	150-375	CIP	SAN	6+
74	30-59	150-375	STP	SAN	0-6
74	30-59	150-375	NC	SAN	0-6
74	30-59	150-375	ACP	SAN	0-6
75	0-29	150-375	ACP	SAN	0-6
75	0-29	150-375	STP	SAN	0-6
75	0-29	150-375	ACP	SAN	6+
75	0-29	150-375	NC	SAN	0-6
75	0-29	150-375	NC	SAN	6+
75	0-29	150-375	CPP	SAN	0-6
75	0-29	150-375	CPP	SAN	6+
76	30-59	450-525	CMP	SAN	0-6
76	30-59	450-525	NC	SAN	0-6
76	30-59	450-525	NC	SAN	6+
77	30-59	150-375	CIP	CMB	0-6
77	30-59	150-375	CMP	CMB	0-6
77	30-59	150-375	NC	CMB	0-6
77	30-59	150-375	CPP	CMB	0-6
78	0-29	150-375	ACP	STM	0-6
78	0-29	150-375	STP	STM	0-6
78	0-29	150-375	CMP	STM	0-6
78	0-29	150-375	NC	STM	0-6
78	0-29	150-375	CPP	STM	0-6
79	0-29	150-375	NC	CMB	6+
79	0-29	150-375	NC	CMB	0-6
80	30-59	150-375	CIP	STM	0-6
80	30-59	150-375	CMP	STM	0-6
80	30-59	150-375	NC	STM	0-6
81	0-29	450-525	STP	STM	0-6
81	0-29	450-525	ACP	STM	0-6

Pipe Class	Age (years)	Diameter (mm)	Material	Waste Type	Ave. Depth of Cover (m)
81	0-29	450-525	CMP	STM	6+
81	0-29	450-525	NC	STM	0-6
82	60+	150-375	CIP	CMB	0-6
82	60+	150-375	NC	CMB	6+
83	0-29	450-525	PEP	SAN	0-6
84	60+	450-525	NC	CMB	0-6
85	0-29	550-600	FRP	STM	0-6
85	0-29	550-600	CMP	STM	0-6
86	30-59	450-525	NC	CMB	0-6
87	30-59	550-600	NC	CMB	0-6
88	60+	550-600	NC	CMB	0-6
89	30-59	450-525	CMP	STM	0-6

APPENDIX C

PIPE MATERIAL CODES

Code	Description
ABS	Acrylonitrile Butadiene Styrene
ACP	Asbestos Cement Pipe
BRK	Brick
CBL	Concrete Block Pipe
CIP	Cast Iron Pipe
CMP	Corrugated Metal Pipe
CON	Poured-In-Place Concrete
CP	Non-Reinforced Concrete Pipe
CPP	Cured-In-Place Pipe
DB	Double Barrel Pipe
DIP	Ductile Iron Pipe
EYE	Eye Pipe
FRP	Fiberglass Reinforced Pipe
NC	Non-Corrode Pipe
ORG	Orangeberg
OVL	Oval Pipe
PEP	Polyethylene Pipe
PLP	Plastic Lined Pipe
PMP	Perferated Metal Pipe
PVC	Polyvinylchloride Pipe
RCP	Reinforced Concrete Pipe
RPM	Reinforced Plastic Mortar Pipe
STP	Steel Pipe
TP	Clay Tile Pipe
VCP	Vitrified Clay Pipe
VSG	Vitrified Segmented Duct
WT	Weeping Tile

APPENDIX D

UNLIMITED BUDGET MODEL OUTPUT

														Program Years	
Pipe Class	Pipe Age (yrs)	Diameter (mm)	Material	Waste	Cover Depth (m)	Length (m)	Effective Length (m)	Size Weight	Waste Weight	Deficiency Prob. %	Pipe Importance Factor	Rehab Cost ($/m)	Applied	Year 1	Year 2
1	30-33	150-375	TP	SAN	0-6	79354.09	22671.46	0.5	0.8	28.57	29.8700	2206.48	1	0	0
2	34-37	150-375	TP	SAN	0-6	93589.00	26738.38	0.5	0.8	28.57	29.8700	2206.48	1	0	0
3	38-40	150-375	TP	SAN	0-6	75169.50	21475.93	0.5	0.8	28.57	29.8700	2206.48	1	0	0
4	41.42	150-375	TP	SAN	0-6	74492.42	21282.48	0.5	0.8	28.57	29.8700	2206.48	1	0	0
5	43-44	150-375	TP	SAN	0-6	55501.27	15856.71	0.5	0.8	28.57	29.8700	2206.48	1	0	0
6	45-59	150-375	TP	SAN	0-6	94065.52	26874.52	0.5	0.8	28.57	29.8700	2206.48	1	0	0
7	0-21	150-375	TP	SAN	0-6	85546.47	50865.93	0.5	0.8	59.46	60.7600	2206.48	1	0	0
8	22-23	150-375	TP	SAN	0-6	94376.38	56116.20	0.5	0.8	59.46	60.7600	2206.48	1	0	0
9	24-25	150-375	TP	SAN	0-6	80570.56	47907.25	0.5	0.8	59.46	60.7600	2206.48	1	0	0
10	26-29	150-375	TP	SAN	0-6	94821.17	56380.67	0.5	0.8	59.46	60.7600	2206.48	1	0	0
11	30-39	150-375	CP	STM	0-6	82958.17	45286.87	0.5	0.5	54.59	55.5900	2206.48	1	0	0
12	40-44	150-375	CP	STM	0-6	93425.14	51000.78	0.5	0.5	54.59	55.5900	2206.48	1	0	0
13	45-59	150-375	CP	STM	0-6	84469.35	46111.82	0.5	0.5	54.59	55.5900	2206.48	1	0	0
14	0-22	150-375	CP	STM	0-6	75337.16	25222.88	0.5	0.5	33.48	34.4800	2206.48	1	0	0
15	23-29	150-375	CP	STM	0-6	84355.17	28242.11	0.5	0.5	33.48	34.4800	2206.48	1	0	0
16	60-85	150-375	TP	CMB	0-6	66037.37	42263.92	0.5	1	64.00	65.5000	2206.48	1	0.311962564	0.199493421
17	86+	150-375	TP	CMB	0-6	65346.09	41821.50	0.5	1	64.00	65.5000	2206.48	1	0	1
18	30-45	150-375	TP	CMB	0-6	38723.34	17150.57	0.5	1	44.29	45.7900	2206.48	1	0	0
19	46-59	150-375	TP	CMB	0-6	77333.51	34251.01	0.5	1	44.29	45.7900	2206.48	1	0	0
20	0-15	150-375	PVC	SAN	0-6	68376.25	24581.26	0.5	0.8	35.95	37.2500	2206.48	1	0	0
21	16-29	150-375	PVC	SAN	0-6	38110.25	13700.63	0.5	0.8	35.95	37.2500	2206.48	1	0	0
22	30-59	150-375	CP	CMB	0-6	73325.79	21367.14	0.5	1	29.14	30.6400	2206.48	1	0	0
23	30-59	450-525	CP	STM	0-6	71944.77	12935.67	0.7	0.5	17.98	19.1800	2206.48	1	0	0
24	0-29	450-525	RCP	STM	0-6	61020.81	13857.83	0.7	0.5	22.71	23.9100	2206.48	1	0	0
25	0-29	150-375	TP	SAN	6+	51188.21	35022.97	0.5	0.8	68.42	69.7200	2206.48	1	1	0
26	0-29	450-525	CP	STM	0-6	50866.21	4277.85	0.7	0.5	8.41	9.6100	2206.48	1	0	0
27	0-29	550-600	RCP	STM	0-6	43275.04	3942.36	1	0.5	9.11	10.6100	2206.48	1	0	0
28	30-59	450-525	CP	CMB	0-6	13941.76	6337.92	0.7	1	45.46	47.1600	2206.48	1	0	0
29	0-29	150-375	RCP	SAN	6+	12037.66	4012.15	0.5	0.8	33.33	34.6300	2206.48	1	0	0
30	30-59	450-525	TP	CMB	0-6	11640.21	1963.70	0.7	1	16.87	18.5700	2206.48	1	0	0
31	30-59	450-525	RCP	CMB	0-6	7749.81	2823.26	0.7	1	36.43	38.1300	2206.48	1	0	0
32	60+	450-525	TP	CMB	0-6	7839.76	2446.79	0.7	1	31.21	32.9100	2206.48	1	0	0
33	30-59	550-600	RCP	CMB	0-6	7015.84	380.96	1	1	5.43	7.4300	2206.48	1	0	0
34	60+	550-600	TP	CMB	0-6	6594.31	1556.26	1	1	23.60	25.6000	2206.48	1	0	0
35	0-29	550-600	CP	STM	0-6	6319.13	1715.64	1	0.5	27.15	28.6500	2206.48	1	0	0
36	0-29	150-375	TP	CMB	0-6	4603.29	2653.80	0.5	1	57.65	59.1500	2206.48	1	0	0
37	30-59	150-375	TP	STM	0-6	3589.67	1958.16	0.5	0.5	54.55	55.5500	2206.48	1	0	0
38	30-59	550-600	TP	CMB	0-6	3225.03	391.52	1	1	12.14	14.1400	2206.48	1	0	0
39	60+	150-375	CP	CMB	0-6	1362.14	1129.21	0.5	1	82.90	84.4000	2206.48	1	1	0
40	60+	150-375	NC	CMB	0-6	746.09	483.91	0.5	1	64.86	66.3600	2206.48	1	1	0
41	30-59	550-600	TP	CMB	6+	729.67	198.11	1	1	27.15	29.1500	2206.48	1	0	0
42	30-59	550-600	CP	CMB	6+	308.05	224.41	1	1	72.85	74.8500	2206.48	1	1	0
43	0-29	150-375	TP	CMB	6+	291.79	145.90	0.5	1	50.00	51.5000	2206.48	1	0	0
44	60+	450-525	CP	CMB	0-6	228.73	207.60	0.7	1	90.76	92.4600	2206.48	1	1	0
45	0-29	450-525	TP	CMB	0-6	193.85	49.97	0.7	1	25.78	27.4800	2206.48	1	0	0
46	0-29	450-525	Variable	SAN	Variable	31966.65	11492.01	0.7	0.8	35.95	37.4500	2206.48	1	0	0
47	0-29	150-375	Variable	SAN	Variable	58086.26	20882.01	0.5	0.8	35.95	37.2500	2206.48	1	0	0
48	0-29	150-375	CP	SAN	0-6	50261.23	18068.91	0.5	0.8	35.95	37.2500	2206.48	1	0	0
49	30-59	150-375	Variable	SAN	Variable	73899.92	25325.50	0.5	0.8	34.27	35.5700	2206.48	1	0	0

Pipe Class	Pipe Age (yrs)	Diameter (mm)	Material	Waste	Cover Depth (m)	Length (m)	Effective Length (m)	Size Weight	Waste Weight	Deficiency Prob. %	Pipe Importance Factor	Rehab Cost ($/m)	Applied	Program Years Year 1	Year 2
50	30-59	450-525	Variable	SAN	Variable	47694.55	16344.92	0.7	0.8	34.27	35.7700	2206.48	1	0	0
51	30-59	550-600	Variable	STM	Variable	38331.59	13136.24	1	0.5	34.27	35.7700	2206.48	1	0	0
52	0-29	150-375	Variable	STM	Variable	36686.56	13188.82	0.5	0.5	35.95	36.9500	2206.48	1	0	0
53	0-29	550-600	Variable	SAN	Variable	12179.10	4378.39	1	0.8	35.95	37.7500	2206.48	1	0	0
54	30-59	550-600	Variable	SAN	Variable	9215.79	3158.25	1	0.8	34.27	36.0700	2206.48	1	0	0
55	0-29	150-375	Variable	CMB	Variable	8486.07	3050.74	0.5	1	35.95	37.4500	2206.48	1	0	0
56	60+	150-375	Variable	SAN	Variable	6450.53	3841.94	0.5	0.8	59.56	60.8600	2206.48	1	0	0
57	30-59	450-525	Variable	STM	Variable	36649.96	12559.94	0.7	0.5	34.27	35.4700	2206.48	1	0	0
58	0-29	450-525	Variable	CMB	Variable	5310.49	1909.12	0.7	1	35.95	37.6500	2206.48	1	0	0
59	30-59	150-375	Variable	CMB	Variable	3852.33	1320.19	0.5	1	34.27	35.7700	2206.48	1	0	0
60	30-59	150-375	Variable	STM	Variable	4503.23	1543.26	0.5	0.5	34.27	35.2700	2206.48	1	0	0
61	0-29	450-525	Variable	STM	Variable	4454.25	1601.30	0.7	0.5	35.95	37.1500	2206.48	1	0	0
62	30-59	450-525	Variable	CMB	Variable	4440.10	1521.62	0.7	1	34.27	35.9700	2206.48	1	0	0
63	60+	150-375	Variable	CMB	6+	3582.02	2133.45	0.5	1	59.56	61.0600	2206.48	1	0	0
64	60+	550-600	Variable	CMB	Variable	3495.87	2082.14	1	1	59.56	61.5600	2206.48	1	0	0
65	30-59	550-600	Variable	CMB	Variable	4056.22	1390.07	1	1	34.27	36.2700	2206.48	1	0	0
66	0-29	550-600	Variable	STM	6+	2801.87	1007.27	1	0.5	35.95	37.4500	2206.48	1	0	0
67	60+	150-375	Variable	STM	Variable	2693.22	1604.08	0.5	0.5	59.56	60.5600	2206.48	1	0	0
68	60+	450-525	TP	CMB	6+	2430.58	1447.65	0.7	1	59.56	61.2600	2206.48	1	0	0
69	0-29	550-600	Variable	CMB	Variable	2350.49	845.00	1	1	35.95	37.9500	2206.48	1	0	0
70	60+	450-525	Variable	STM	Variable	417.58	248.71	0.7	0.5	59.56	60.7600	2206.48	1	0	0
71	60+	550-600	Variable	STM	Variable	281.63	167.74	1	0.5	59.56	61.0600	2206.48	1	0	0
72	60+	450-525	TP	SAN	Variable	267.61	159.39	0.7	0.8	59.56	61.0600	2206.48	1	0	0
73	60+	550-600	TP	SAN	6+	98.54	58.69	1	0.8	59.56	61.3600	2206.48	1	0	0
74	30-59	150-375	Variable	SAN	Variable	3632.78	1244.95	0.5	0.8	34.27	35.5700	2206.48	1	0	0
75	0-29	150-375	Variable	SAN	Variable	5642.94	2028.64	0.5	0.8	35.95	37.2500	2206.48	1	0	0
76	30-59	450-525	Variable	SAN	Variable	987.09	338.28	0.7	0.8	34.27	35.7700	2206.48	1	0	0
77	30-59	150-375	Variable	CMB	0-6	646.07	221.41	0.5	1	34.27	35.7700	2206.48	1	0	0
78	0-29	150-375	Variable	STM	0-6	623.04	223.98	0.5	0.5	35.95	36.9500	2206.48	1	0	0
79	0-29	150-375	NC	CMB	Variable	443.77	159.54	0.5	1	35.95	37.4500	2206.48	1	0	0
80	30-59	150-375	Variable	STM	0-6	402.24	137.85	0.5	0.5	34.27	35.2700	2206.48	1	0	0
81	0-29	450-525	Variable	STM	Variable	160.01	57.52	0.7	0.5	35.95	37.1500	2206.48	1	0	0
82	60+	150-375	Variable	CMB	Variable	151.64	90.32	0.5	1	59.56	61.0600	2206.48	1	0	0
83	0-29	450-525	PEP	SAN	0-6	149.04	53.58	0.7	0.8	35.95	37.4500	2206.48	1	0	0
84	60+	450-525	NC	CMB	0-6	94.81	56.47	0.7	1	59.56	61.2600	2206.48	1	0	0
85	0-29	550-600	Variable	STM	0-6	66.91	24.05	1	0.5	35.95	37.4500	2206.48	1	0	0
86	30-59	450-525	NC	CMB	0-6	54.00	18.51	0.7	1	34.27	35.9700	2206.48	1	0	0
87	30-59	550-600	NC	CMB	0-6	52.12	17.86	1	1	34.27	36.2700	2206.48	1	0	0
88	60+	550-600	NC	CMB	0-6	48.77	29.05	1	1	59.56	61.5600	2206.48	1	0	0
89	30-59	450-525	CMP	STM	0-6	6.10	2.09	0.7	0.5	34.27	35.4700	2206.48	1	0	0
													Annual Expenditure	110,881,954.70	110,881,954.65
													Annual Budget	110,881,954.65	110,881,954.65

Pipe Class	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13
1	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0
7	0.384112818	0	0	0.615887182	0	0	0	0	0	0	0
8	0	0.041799269	0	0.337250161	0.62095057	0	0	0	0	0	0
9	0	1	0	0	0	0	0	0	0	0	0
10	0	0	0.886902592	0	0.113097408	0	0	0	0	0	0
11	0	0	0	0	0	0.088882028	0.911117972	0	0	0	0
12	0	0	0	0	0.093588785	0.906411215	0	0	0	0	0
13	0	0	0	0	0	0	0.194986767	0.805013233	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0
16	0.488544015	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0.273475679	0.726524321	0	0
19	0	0	0	0	0	0	0	0	1	0	0
20	0	0	0	0	0	0	0	0	0	0	0.96106309
21	0	0	0	0	0	0	0	0	0	0.375224921	0.624775079
22	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	1	0	0	0
29	0	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	0
31	0	0	0	0	0	0	0	0	1	0	0
32	0	0	0	0	0	0	0	0	0	0	0
33	0	0	0	0	0	0	0	0	0	0	0
34	0	0	0	0	0	0	0	0	0	0	0
35	0	0	0	0	0	0	0	0	0	0	0
36	0	0	0	0	1	0	0	0	0	0	0
37	0	0	0	0	0	0	0	1	0	0	0
38	0	0	0	0	0	0	0	0	0	0	0
39	0	0	0	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0	0	0	0	0
41	0	0	0	0	0	0	0	0	0	0	0
42	0	0	0	0	0	0	0	0	0	0	0
43	0	0	0	0	0	0	0	1	0	0	0
44	0	0	0	0	0	0	0	0	0	0	0
45	0	0	0	0	0	0	0	0	0	0	0
46	0	0	0	0	0	0	0	0	0	1	0
47	0	0	0	0	0	0	0	0	0	1	0
48	0	0	0	0	0	0	0	0	0	0	1
49	0	0	0	0	0	0	0	0	0	0	0

Pipe Class	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13
50	0	0	0	0	0	0	0	0	0	0	0
51	0	0	0	0	0	0	0	0	0	0	0
52	0	0	0	0	0	0	0	0	0	0	0
53	0	0	0	0	0	0	0	0	0	1	0
54	0	0	0	0	0	0	0	0	0	0	0
55	0	0	0	0	0	0	0	0	0	1	0
56	1	0	0	0	0	0	0	0	0	0	0
57	0	0	0	0	0	0	0	0	0	0	0
58	0	0	0	0	0	0	0	0	0	1	0
59	0	0	0	0	0	0	0	0	0	0	0
60	0	0	0	0	0	0	0	0	0	0	0
61	0	0	0	0	0	0	0	0	0	0	0
62	0	0	0	0	0	0	0	0	0	0	0
63	1	0	0	0	0	0	0	0	0	0	0
64	1	0	0	0	0	0	0	0	0	0	0
65	0	0	0	0	0	0	0	0	0	0	0
66	0	0	0	0	0	0	0	0	0	1	0
67	0	0	0	0	1	0	0	0	0	0	0
68	1	0	0	0	0	0	0	0	0	0	0
69	0	0	0	0	0	0	0	0	0.850057193	0.149942807	0
70	0	0	1	0	0	0	0	0	0	0	0
71	1	0	0	0	0	0	0	0	0	0	0
72	1	0	0	0	0	0	0	0	0	0	0
73	1	0	0	0	0	0	0	0	0	0	0
74	0	0	0	0	0	0	0	0	0	0	0
75	0	0	0	0	0	0	0	0	0	1	0
76	0	0	0	0	0	0	0	0	0	0	0
77	0	0	0	0	0	0	0	0	0	0	0
78	0	0	0	0	0	0	0	0	0	0	0
79	0	0	0	0	0	0	0	0	0	1	0
80	0	0	0	0	0	0	0	0	0	0	0
81	0	0	0	0	0	0	0	0	0	0	0
82	1	0	0	0	0	0	0	0	0	0	0
83	0	0	0	0	0	0	0	0	0	1	0
84	1	0	0	0	0	0	0	0	0	0	0
85	0	0	0	0	0	0	0	0	0	1	0
86	0	0	0	0	0	0	0	0	0	0	0
87	0	0	0	0	0	0	0	0	0	0	0
88	1	0	0	0	0	0	0	0	0	0	0
89	0	0	0	0	0	0	0	0	0	0	0
	110,881,954.65	110,881,954.65	110,881,954.65	110,881,954.65	110,881,954.65	110,881,954.65	110,881,954.65	110,881,954.65	110,881,954.65	110,881,954.65	110,881,954.65
	110,881,954.65	110,881,954.65	110,881,954.65	110,881,954.65	110,881,954.65	110,881,954.65	110,881,954.65	110,881,954.65	110,881,954.65	110,881,954.65	110,881,954.65

Pipe Class	Year 14	Year 15	Year 16	Year 17	Year 18	Year 19	Year 20
1	0	0	0	0	1	0	0
2	0	0	0	0	0	0.664040651	0.335959349
3	0	0	0	0	0	1	0
4	0	0	0	1	0	0	0
5	0	0	0	0.260347098	0.739652902	0	0
6	0	0	0	0	0.589887533	0.410112467	0
7	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0
14	0	0.086584403	0.913415597	0	0	0	0
15	0	0	0.963592911	0.036407089	0	0	0
16	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0
20	0.03893691	0	0	0	0	0	0
21	0	0	0	0	0	0	0
22	0	0	0	1	0	0	0
23	0	0	0	0	0	0	1
24	0	0	0	0	0	0	1
25	0	0	0	0	0	0	0
26	0	0	0	0	0	0	1
27	0	0	0	0	0	0	1
28	0	0	0	0	0	0	0
29	0	1	0	0	0	0	0
30	0	0	0	0	0	0	1
31	0	0	0	0	0	0	0
32	0	0	0	1	0	0	0
33	0	0	0	0	0	0	1
34	0	0	0	0	0	0	1
35	0	0	0	0	0	0	1
36	0	0	0	0	0	0	0
37	0	0	0	0	0	0	0
38	0	0	0	0	0	0	1
39	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0
41	0	0	0	0	0	0	1
42	0	0	0	0	0	0	0
43	0	0	0	0	0	0	0
44	0	0	0	0	0	0	0
45	0	0	0	0	0	0	1
46	0	0	0	0	0	0	0
47	0	0	0	0	0	0	0
48	0	0	0	0	0	0	0
49	0	1	0	0	0	0	0

Pipe Class	Year 14	Year 15	Year 16	Year 17	Year 18	Year 19	Year 20
50	0.903043351	0.096956649	0	0	0	0	0
51	1	0	0	0	0	0	0
52	1	0	0	0	0	0	0
53	0	0	0	0	0	0	0
54	1	0	0	0	0	0	0
55	0	0	0	0	0	0	0
56	0	0	0	0	0	0	0
57	0	1	0	0	0	0	0
58	0	0	0	0	0	0	0
59	0	1	0	0	0	0	0
60	0	1	0	0	0	0	0
61	1	0	0	0	0	0	0
62	1	0	0	0	0	0	0
63	0	0	0	0	0	0	0
64	0	0	0	0	0	0	0
65	1	0	0	0	0	0	0
66	0	0	0	0	0	0	0
67	0	0	0	0	0	0	0
68	0	0	0	0	0	0	0
69	0	0	0	0	0	0	0
70	0	0	0	0	0	0	0
71	0	0	0	0	0	0	0
72	0	0	0	0	0	0	0
73	0	0	0	0	0	0	0
74	0	1	0	0	0	0	0
75	0	0	0	0	0	0	0
76	0	1	0	0	0	0	0
77	1	0	0	0	0	0	0
78	1	0	0	0	0	0	0
79	0	0	0	0	0	0	0
80	0	1	0	0	0	0	0
81	1	0	0	0	0	0	0
82	0	0	0	0	0	0	0
83	0	0	0	0	0	0	0
84	0	0	0	0	0	0	0
85	0	0	0	0	0	0	0
86	1	0	0	0	0	0	0
87	1	0	0	0	0	0	0
88	0	0	0	0	0	0	0
89	0	1	0	0	0	0	0
	110,881,954.65	110,881,954.65	110,881,954.65	110,881,954.65	110,881,954.65	110,881,954.65	110,881,954.58
	110,881,954.65	110,881,954.65	110,881,954.65	110,881,954.65	110,881,954.65	110,881,954.65	110,881,954.65
							Total $ 2,217,639,092.98

APPENDIX E

REALISTIC BUDGET MODEL OUTPUT

Pipe Class	Pipe Age (yrs)	Diameter (mm)	Material	Waste	Cover Depth (m)	Length (m)	Effective Length (m)	Size Weight	Waste Weight	Deficiency Prob. %	Pipe Importance Factor	Rehab Cost ($/m)	Applied	Program Years Year 1	Year 2
1	30-33	150-375	TP	SAN	0-6	79354.09	22671.46	0.5	0.8	28.57	29.870000	2206.48	1	0	0
2	34-37	150-375	TP	SAN	0-6	93589.00	26738.38	0.5	0.8	28.57	29.870000	2206.48	1	0	0
3	38-40	150-375	TP	SAN	0-6	75169.50	21475.93	0.5	0.8	28.57	29.870000	2206.48	1	0	0
4	41.42	150-375	TP	SAN	0-6	74492.42	21282.48	0.5	0.8	28.57	29.870000	2206.48	1	0	0
5	43-44	150-375	TP	SAN	0-6	55501.27	15856.71	0.5	0.8	28.57	29.870000	2206.48	1	0	0
6	45-59	150-375	TP	SAN	0-6	94065.52	26874.52	0.5	0.8	28.57	29.870000	2206.48	1	0	0
7	0-21	150-375	TP	SAN	0-6	85546.47	50865.93	0.5	0.8	59.46	60.760000	2206.48	1	0	0
8	22-23	150-375	TP	SAN	0-6	94376.38	56116.20	0.5	0.8	59.46	60.760000	2206.48	1	0	0
9	24-25	150-375	TP	SAN	0-6	80570.56	47907.25	0.5	0.8	59.46	60.760000	2206.48	1	0	0
10	26-29	150-375	TP	SAN	0-6	94821.17	56380.67	0.5	0.8	59.46	60.760000	2206.48	1	0	0
11	30-39	150-375	CP	STM	0-6	82958.17	45286.87	0.5	0.5	54.59	55.590000	2206.48	1	0	0
12	40-44	150-375	CP	STM	0-6	93425.14	51000.78	0.5	0.5	54.59	55.590000	2206.48	1	0	0
13	45-59	150-375	CP	STM	0-6	84469.35	46111.82	0.5	0.5	54.59	55.590000	2206.48	1	0	0
14	0-22	150-375	CP	STM	0-6	75337.16	25222.88	0.5	0.5	33.48	34.480000	2206.48	1	0	0
15	23-29	150-375	CP	STM	0-6	84355.17	28242.11	0.5	0.5	33.48	34.480000	2206.48	1	0	0
16	60-85	150-375	TP	CMB	0-6	66037.37	42263.92	0.5	1	64.00	65.500000	2206.48	1	0	0
17	86+	150-375	TP	CMB	0-6	65346.09	41821.50	0.5	1	64.00	65.500000	2206.48	1	0	0
18	30-45	150-375	TP	CMB	0-6	38723.34	17150.57	0.5	1	44.29	45.790000	2206.48	1	0	0
19	46-59	150-375	TP	CMB	0-6	77333.51	34251.01	0.5	1	44.29	45.790000	2206.48	1	0	0
20	0-15	150-375	PVC	SAN	0-6	68376.25	24581.26	0.5	0.8	35.95	37.250000	2206.48	1	0	0
21	16-29	150-375	PVC	SAN	0-6	38110.25	13700.63	0.5	0.8	35.95	37.250000	2206.48	1	0	0
22	30-59	150-375	CP	CMB	0-6	73325.79	21367.14	0.5	1	29.14	30.640000	2206.48	1	0	0
23	30-59	450-525	CP	STM	0-6	71944.77	12935.67	0.7	0.5	17.98	19.180000	2206.48	1	0	0
24	0-29	450-525	RCP	STM	0-6	61020.81	13857.83	0.7	0.5	22.71	23.910000	2206.48	1	0	0
25	0-29	150-375	TP	SAN	6+	51188.21	35022.97	0.5	0.8	68.42	69.720000	2206.48	1	0	0
26	0-29	450-525	CP	STM	0-6	50866.21	4277.85	0.7	0.5	8.41	9.610000	2206.48	1	0	0
27	0-29	550-600	RCP	STM	0-6	43275.04	3942.36	1	0.5	9.11	10.610000	2206.48	1	0	0
28	30-59	450-525	CP	CMB	0-6	13941.76	6337.92	0.7	1	45.46	47.160000	2206.48	1	0	0
29	0-29	150-375	RCP	SAN	6+	12037.66	4012.15	0.5	0.8	33.33	34.630000	2206.48	1	0	0
30	30-59	450-525	TP	CMB	0-6	11640.21	1963.70	0.7	1	16.87	18.570000	2206.48	1	0	0
31	30-59	450-525	RCP	CMB	0-6	7749.81	2823.26	0.7	1	36.43	38.130000	2206.48	1	0	0
32	60+	450-525	TP	CMB	0-6	7839.76	2446.79	0.7	1	31.21	32.910000	2206.48	1	0	0
33	30-59	550-600	RCP	CMB	0-6	7015.84	380.96	1	1	5.43	7.430000	2206.48	1	0	0
34	60+	550-600	TP	CMB	0-6	6594.31	1556.26	1	1	23.60	25.600000	2206.48	1	0	0
35	0-29	550-600	CP	STM	0-6	6319.13	1715.64	1	0.5	27.15	28.650000	2206.48	1	0	0
36	0-29	150-375	TP	CMB	0-6	4603.29	2653.80	0.5	1	57.65	59.150000	2206.48	1	0	0
37	30-59	150-375	TP	STM	0-6	3589.67	1958.16	0.5	0.5	54.55	55.550000	2206.48	1	0	0
38	30-59	550-600	TP	CMB	0-6	3225.03	391.52	1	1	12.14	14.140000	2206.48	1	0	0
39	60+	150-375	CP	CMB	0-6	1362.14	1129.21	0.5	1	82.90	84.400000	2206.48	1	0.42583447	0.57416553
40	60+	150-375	NC	CMB	0-6	746.09	483.91	0.5	1	64.86	66.360000	2206.48	1	0	0
41	30-59	550-600	TP	CMB	6+	729.67	198.11	1	1	27.15	29.150000	2206.48	1	0	0
42	30-59	550-600	CP	CMB	6+	308.05	224.41	1	1	72.85	74.850000	2206.48	1	0	0.274952246
43	0-29	150-375	TP	CMB	6+	291.79	145.90	0.5	1	50.00	51.500000	2206.48	1	0	0
44	60+	450-525	CP	CMB	0-6	228.73	207.60	0.7	1	90.76	92.460000	2206.48	1	1	0
45	0-29	450-525	TP	CMB	0-6	193.85	49.97	0.7	1	25.78	27.480000	2206.48	1	0	0
46	0-29	450-525	Variable	SAN	Variable	31966.65	11492.01	0.7	0.8	35.95	37.450000	2206.48	1	0	0
47	0-29	150-375	Variable	SAN	Variable	58086.26	20882.01	0.5	0.8	35.95	37.250000	2206.48	1	0	0

Pipe Class	Pipe Age (yrs)	Diameter (mm)	Material	Waste	Cover Depth (m)	Length (m)	Effective Length (m)	Size Weight	Waste Weight	Deficiency Prob. %	Pipe Importance Factor	Rehab Cost ($/m)	Applied	Program Years Year 1	Year 2
48	0-29	150-375	CP	SAN	0-6	50261.23	18068.91	0.5	0.8	35.95	37.250000	2206.48	1	0	0
49	30-59	150-375	Variable	SAN	Variable	73899.92	25325.50	0.5	0.8	34.27	35.570000	2206.48	1	0	0
50	30-59	450-525	Variable	SAN	Variable	47694.55	16344.92	0.7	0.8	34.27	35.770000	2206.48	1	0	0
51	30-59	550-600	Variable	STM	Variable	38331.59	13136.24	1	0.5	34.27	35.770000	2206.48	1	0	0
52	0-29	150-375	Variable	STM	Variable	36686.56	13188.82	0.5	0.5	35.95	36.950000	2206.48	1	0	0
53	0-29	550-600	Variable	SAN	Variable	12179.10	4378.39	1	0.8	35.95	37.750000	2206.48	1	0	0
54	30-59	550-600	Variable	SAN	Variable	9215.79	3158.25	1	0.8	34.27	36.070000	2206.48	1	0	0
55	0-29	150-375	Variable	CMB	Variable	8486.07	3050.74	0.5	1	35.95	37.450000	2206.48	1	0	0
56	60+	150-375	Variable	SAN	Variable	6450.53	3841.94	0.5	0.8	59.56	60.860000	2206.48	1	0	0
57	30-59	450-525	Variable	STM	Variable	36649.96	12559.94	0.7	0.5	34.27	35.470000	2206.48	1	0	0
58	0-29	450-525	Variable	CMB	Variable	5310.49	1909.12	0.7	1	35.95	37.650000	2206.48	1	0	0
59	30-59	150-375	Variable	CMB	Variable	3852.33	1320.19	0.5	1	34.27	35.770000	2206.48	1	0	0
60	30-59	150-375	Variable	STM	Variable	4503.23	1543.26	0.5	0.5	34.27	35.270000	2206.48	1	0	0
61	0-29	450-525	Variable	STM	Variable	4454.25	1601.30	0.7	0.5	35.95	37.150000	2206.48	1	0	0
62	30-59	450-525	Variable	CMB	Variable	4440.10	1521.62	0.7	1	34.27	35.970000	2206.48	1	0	0
63	60+	150-375	Variable	CMB	6+	3582.02	2133.45	0.5	1	59.56	61.060000	2206.48	1	0	0
64	60+	550-600	Variable	CMB	Variable	3495.87	2082.14	1	1	59.56	61.560000	2206.48	1	0	0
65	30-59	550-600	Variable	CMB	Variable	4056.22	1390.07	1	1	34.27	36.270000	2206.48	1	0	0
66	0-29	550-600	Variable	STM	6+	2801.87	1007.27	1	0.5	35.95	37.450000	2206.48	1	0	0
67	60+	150-375	Variable	STM	Variable	2693.22	1604.08	0.5	0.5	59.56	60.560000	2206.48	1	0	0
68	60+	450-525	TP	CMB	6+	2430.58	1447.65	0.7	1	59.56	61.260000	2206.48	1	0	0
69	0-29	550-600	Variable	CMB	Variable	2350.49	845.00	1	1	35.95	37.950000	2206.48	1	0	0
70	60+	450-525	Variable	STM	Variable	417.58	248.71	0.7	0.5	59.56	60.760000	2206.48	1	0	0
71	60+	550-600	Variable	STM	Variable	281.63	167.74	1	0.5	59.56	61.060000	2206.48	1	0	0
72	60+	450-525	TP	SAN	Variable	267.61	159.39	0.7	0.8	59.56	61.060000	2206.48	1	0	0
73	60+	550-600	TP	SAN	6+	98.54	58.69	1	0.8	59.56	61.360000	2206.48	1	0	0
74	30-59	150-375	Variable	SAN	Variable	3632.78	1244.95	0.5	0.8	34.27	35.570000	2206.48	1	0	0
75	0-29	150-375	Variable	SAN	Variable	5642.94	2028.64	0.5	0.8	35.95	37.250000	2206.48	1	0	0
76	30-59	450-525	Variable	SAN	Variable	987.09	338.28	0.7	0.8	34.27	35.770000	2206.48	1	0	0
77	30-59	150-375	Variable	CMB	0-6	646.07	221.41	0.5	1	34.27	35.770000	2206.48	1	0	0
78	0-29	150-375	Variable	STM	0-6	623.04	223.98	0.5	0.5	35.95	36.950000	2206.48	1	0	0
79	0-29	150-375	NC	CMB	Variable	443.77	159.54	0.5	1	35.95	37.450000	2206.48	1	0	0
80	30-59	150-375	Variable	STM	0-6	402.24	137.85	0.5	0.5	34.27	35.270000	2206.48	1	0	0
81	0-29	450-525	Variable	STM	Variable	160.01	57.52	0.7	0.5	35.95	37.150000	2206.48	1	0	0
82	60+	150-375	Variable	CMB	Variable	151.64	90.32	0.5	1	59.56	61.060000	2206.48	1	0	0
83	0-29	450-525	PEP	SAN	0-6	149.04	53.58	0.7	0.8	35.95	37.450000	2206.48	1	0	0
84	60+	450-525	NC	CMB	0-6	94.81	56.47	0.7	1	59.56	61.260000	2206.48	1	0	0
85	0-29	550-600	Variable	STM	0-6	66.91	24.05	1	0.5	35.95	37.450000	2206.48	1	0	0
86	30-59	450-525	NC	CMB	0-6	54.00	18.51	0.7	1	34.27	35.970000	2206.48	1	0	0
87	30-59	550-600	NC	CMB	0-6	52.12	17.86	1	1	34.27	36.270000	2206.48	1	0	0
88	60+	550-600	NC	CMB	0-6	48.77	29.05	1	1	59.56	61.560000	2206.48	1	0	0
89	30-59	450-525	CMP	STM	0-6	6.10	2.09	0.7	0.5	34.27	35.470000	2206.48	1	0	0
													Annual Expenditure	1,519,059.14	1,566,731.07
													Annual Budget	1,519,059.14	1,566,731.07

Pipe Class	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0
25	0.016245145	0.021507879	0.022124772	0.022741665	0.023358558	0.02397545	0.024592343	0.025209236	0.025826129	0.026443022	0.027059914	0.027676807
26	0	0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	0	0
31	0	0	0	0	0	0	0	0	0	0	0	0
32	0	0	0	0	0	0	0	0	0	0	0	0
33	0	0	0	0	0	0	0	0	0	0	0	0
34	0	0	0	0	0	0	0	0	0	0	0	0
35	0	0	0	0	0	0	0	0	0	0	0	0
36	0	0	0	0	0	0	0	0	0	0	0	0
37	0	0	0	0	0	0	0	0	0	0	0	0
38	0	0	0	0	0	0	0	0	0	0	0	0
39	0	0	0	0	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0	0	0	0	0	0
41	0	0	0	0	0	0	0	0	0	0	0	0
42	0.725047754	0	0	0	0	0	0	0	0	0	0	0
43	0	0	0	0	0	0	0	0	0	0	0	0
44	0	0	0	0	0	0	0	0	0	0	0	0
45	0	0	0	0	0	0	0	0	0	0	0	0
46	0	0	0	0	0	0	0	0	0	0	0	0
47	0	0	0	0	0	0	0	0	0	0	0	0

Pipe Class	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14
48	0	0	0	0	0	0	0	0	0	0	0	0
49	0	0	0	0	0	0	0	0	0	0	0	0
50	0	0	0	0	0	0	0	0	0	0	0	0
51	0	0	0	0	0	0	0	0	0	0	0	0
52	0	0	0	0	0	0	0	0	0	0	0	0
53	0	0	0	0	0	0	0	0	0	0	0	0
54	0	0	0	0	0	0	0	0	0	0	0	0
55	0	0	0	0	0	0	0	0	0	0	0	0
56	0	0	0	0	0	0	0	0	0	0	0	0
57	0	0	0	0	0	0	0	0	0	0	0	0
58	0	0	0	0	0	0	0	0	0	0	0	0
59	0	0	0	0	0	0	0	0	0	0	0	0
60	0	0	0	0	0	0	0	0	0	0	0	0
61	0	0	0	0	0	0	0	0	0	0	0	0
62	0	0	0	0	0	0	0	0	0	0	0	0
63	0	0	0	0	0	0	0	0	0	0	0	0
64	0	0	0	0	0	0	0	0	0	0	0	0
65	0	0	0	0	0	0	0	0	0	0	0	0
66	0	0	0	0	0	0	0	0	0	0	0	0
67	0	0	0	0	0	0	0	0	0	0	0	0
68	0	0	0	0	0	0	0	0	0	0	0	0
69	0	0	0	0	0	0	0	0	0	0	0	0
70	0	0	0	0	0	0	0	0	0	0	0	0
71	0	0	0	0	0	0	0	0	0	0	0	0
72	0	0	0	0	0	0	0	0	0	0	0	0
73	0	0	0	0	0	0	0	0	0	0	0	0
74	0	0	0	0	0	0	0	0	0	0	0	0
75	0	0	0	0	0	0	0	0	0	0	0	0
76	0	0	0	0	0	0	0	0	0	0	0	0
77	0	0	0	0	0	0	0	0	0	0	0	0
78	0	0	0	0	0	0	0	0	0	0	0	0
79	0	0	0	0	0	0	0	0	0	0	0	0
80	0	0	0	0	0	0	0	0	0	0	0	0
81	0	0	0	0	0	0	0	0	0	0	0	0
82	0	0	0	0	0	0	0	0	0	0	0	0
83	0	0	0	0	0	0	0	0	0	0	0	0
84	0	0	0	0	0	0	0	0	0	0	0	0
85	0	0	0	0	0	0	0	0	0	0	0	0
86	0	0	0	0	0	0	0	0	0	0	0	0
87	0	0	0	0	0	0	0	0	0	0	0	0
88	0	0	0	0	0	0	0	0	0	0	0	0
89	0	0	0	0	0	0	0	0	0	0	0	0
	1,614,402.99	1,662,074.92	1,709,746.85	1,757,418.77	1,805,090.70	1,852,762.63	1,900,434.56	1,948,106.48	1,995,778.41	2,043,450.34	2,091,122.27	2,138,794.19
	1,614,402.99	1,662,074.92	1,709,746.85	1,757,418.77	1,805,090.70	1,852,762.63	1,900,434.56	1,948,106.48	1,995,778.41	2,043,450.34	2,091,122.27	2,138,794.19

Pipe Class	Year 15	Year 16	Year 17	Year 18	Year 19	Year 20	SURPLUS
1	0	0	0	0	0	0	1
2	0	0	0	0	0	0	1
3	0	0	0	0	0	0	1
4	0	0	0	0	0	0	1
5	0	0	0	0	0	0	1
6	0	0	0	0	0	0	1
7	0	0	0	0	0	0	1
8	0	0	0	0	0	0	1
9	0	0	0	0	0	0	1
10	0	0	0	0	0	0	1
11	0	0	0	0	0	0	1
12	0	0	0	0	0	0	1
13	0	0	0	0	0	0	1
14	0	0	0	0	0	0	1
15	0	0	0	0	0	0	1
16	0	0	0	0	0	0	1
17	0	0	0	0	0	0	1
18	0	0	0	0	0	0	1
19	0	0	0	0	0	0	1
20	0	0	0	0	0	0	1
21	0	0	0	0	0	0	1
22	0	0	0	0	0	0	1
23	0	0	0	0	0	0	1
24	0	0	0	0	0	0	1
25	0.0282937	0.028910593	0.029527486	0.030144378	0.030761271	0.031378164	0.534223488
26	0	0	0	0	0	0	1
27	0	0	0	0	0	0	1
28	0	0	0	0	0	0	1
29	0	0	0	0	0	0	1
30	0	0	0	0	0	0	1
31	0	0	0	0	0	0	1
32	0	0	0	0	0	0	1
33	0	0	0	0	0	0	1
34	0	0	0	0	0	0	1
35	0	0	0	0	0	0	1
36	0	0	0	0	0	0	1
37	0	0	0	0	0	0	1
38	0	0	0	0	0	0	1
39	0	0	0	0	0	0	0
40	0	0	0	0	0	0	1
41	0	0	0	0	0	0	1
42	0	0	0	0	0	0	0
43	0	0	0	0	0	0	1
44	0	0	0	0	0	0	0
45	0	0	0	0	0	0	1
46	0	0	0	0	0	0	1
47	0	0	0	0	0	0	1

Pipe Class	Year 15	Year 16	Year 17	Year 18	Year 19	Year 20	SURPLUS
48	0	0	0	0	0	0	1
49	0	0	0	0	0	0	1
50	0	0	0	0	0	0	1
51	0	0	0	0	0	0	1
52	0	0	0	0	0	0	1
53	0	0	0	0	0	0	1
54	0	0	0	0	0	0	1
55	0	0	0	0	0	0	1
56	0	0	0	0	0	0	1
57	0	0	0	0	0	0	1
58	0	0	0	0	0	0	1
59	0	0	0	0	0	0	1
60	0	0	0	0	0	0	1
61	0	0	0	0	0	0	1
62	0	0	0	0	0	0	1
63	0	0	0	0	0	0	1
64	0	0	0	0	0	0	1
65	0	0	0	0	0	0	1
66	0	0	0	0	0	0	1
67	0	0	0	0	0	0	1
68	0	0	0	0	0	0	1
69	0	0	0	0	0	0	1
70	0	0	0	0	0	0	1
71	0	0	0	0	0	0	1
72	0	0	0	0	0	0	1
73	0	0	0	0	0	0	1
74	0	0	0	0	0	0	1
75	0	0	0	0	0	0	1
76	0	0	0	0	0	0	1
77	0	0	0	0	0	0	1
78	0	0	0	0	0	0	1
79	0	0	0	0	0	0	1
80	0	0	0	0	0	0	1
81	0	0	0	0	0	0	1
82	0	0	0	0	0	0	1
83	0	0	0	0	0	0	1
84	0	0	0	0	0	0	1
85	0	0	0	0	0	0	1
86	0	0	0	0	0	0	1
87	0	0	0	0	0	0	1
88	0	0	0	0	0	0	1
89	0	0	0	0	0	0	1
	2,186,466.12	2,234,138.05	2,281,809.98	2,329,481.90	2,377,153.83	2,424,825.76	2,178,200,244.02
	2,186,466.12	2,234,138.05	2,281,809.98	2,329,481.90	2,377,153.83	2,424,825.76	3,000,000,000.00

APPENDIX F

ENTIRE SEWER INSPECTION MODEL OUTPUT

Pipe Class	Pipe Age (yrs)	Diameter (mm)	Material	Waste	Cover Depth (m)	Length (m)	Size Weight	Waste Weight	Deficiency Prob. %	Pipe Importance Factor	Applied	Program Years Year 1	Year 2	Year 3	Year 4
1	30-33	150-375	TP	SAN	0-6	79354.09	0.50	0.8	28.57	0.000914	1	0	0	0	0
2	34-37	150-375	TP	SAN	0-6	93589.00	0.50	0.8	28.57	0.000914	1	0	0	0	0
3	38-40	150-375	TP	SAN	0-6	75169.50	0.50	0.8	28.57	0.000914	1	0	0	0	0
4	41.42	150-375	TP	SAN	0-6	74492.42	0.50	0.8	28.57	0.000914	1	0	0	0	0
5	43-44	150-375	TP	SAN	0-6	55501.27	0.50	0.8	28.57	0.000914	1	0	0	0	0
6	45-59	150-375	TP	SAN	0-6	94065.52	0.50	0.8	28.57	0.000914	1	0	0	0	0
7	0-21	150-375	TP	SAN	0-6	85546.47	0.50	0.8	59.46	0.001903	1	0	1	0	0
8	22-23	150-375	TP	SAN	0-6	94376.38	0.50	0.8	59.46	0.001903	1	0	0	1	0
9	24-25	150-375	TP	SAN	0-6	80570.56	0.50	0.8	59.46	0.001903	1	0	0	1	0
10	26-29	150-375	TP	SAN	0-6	94821.17	0.50	0.8	59.46	0.001903	1	0	0.921315567	0.078684433	0
11	30-39	150-375	CP	STM	0-6	82958.17	0.50	0.5	54.59	0.001092	1	0	0	0	0
12	40-44	150-375	CP	STM	0-6	93425.14	0.50	0.5	54.59	0.001092	1	0	0	0	0
13	45-59	150-375	CP	STM	0-6	84469.35	0.50	0.5	54.59	0.001092	1	0	0	0	0
14	0-22	150-375	CP	STM	0-6	75337.16	0.50	0.5	33.48	0.000670	1	0	0	0	0
15	23-29	150-375	CP	STM	0-6	84355.17	0.50	0.5	33.48	0.000670	1	0	0	0	0
16	60-85	150-375	TP	CMB	0-6	66037.37	0.50	1	64	0.002560	1	1	0	0	0
17	86+	150-375	TP	CMB	0-6	65346.09	0.50	1	64	0.002560	1	1	0	0	0
18	30-45	150-375	TP	CMB	0-6	38723.34	0.50	1	44.29	0.001772	1	0	0	0	1
19	46-59	150-375	TP	CMB	0-6	77333.51	0.50	1	44.29	0.001772	1	0	0	0.400832706	0.599167294
20	0-15	150-375	PVC	SAN	0-6	68376.25	0.50	0.8	35.95	0.001150	1	0	0	0	0
21	16-29	150-375	PVC	SAN	0-6	38110.25	0.50	0.8	35.95	0.001150	1	0	0	0	0
22	30-59	150-375	CP	CMB	0-6	73325.79	0.50	1	29.14	0.001166	1	0	0	0	0
23	30-59	450-525	CP	STM	0-6	71944.77	0.70	0.5	17.98	0.000503	1	0	0	0	0
24	0-29	450-525	RCP	STM	0-6	61020.81	0.70	0.5	22.71	0.000636	1	0	0	0	0
25	0-29	150-375	TP	SAN	6+	51188.21	0.50	0.8	68.42	0.002189	1	0.568906199	0.431093801	0	0
26	0-29	450-525	CP	STM	0-6	50866.21	0.70	0.5	8.41	0.000235	1	0	0	0	0
27	0-29	550-600	RCP	STM	0-6	43275.04	1.00	0.5	9.11	0.000364	1	0	0	0	0
28	30-59	450-525	CP	CMB	0-6	13941.76	0.70	1	45.46	0.002546	1	1	0	0	0
29	0-29	150-375	RCP	SAN	6+	12037.66	0.50	0.8	33.33	0.001067	1	0	0	0	0
30	30-59	450-525	TP	CMB	0-6	11640.21	0.70	1	16.87	0.000945	1	0	0	0	0
31	30-59	450-525	RCP	CMB	0-6	7749.81	0.70	1	36.43	0.002040	1	0	1	0	0
32	60+	450-525	TP	CMB	0-6	7839.76	0.70	1	31.21	0.001748	1	0	0	0	1
33	30-59	550-600	RCP	CMB	0-6	7015.84	1.00	1	5.43	0.000434	1	0	0	0	0
34	60+	550-600	TP	CMB	0-6	6594.31	1.00	1	23.6	0.001888	1	0	0	1	0
35	0-29	550-600	CP	STM	0-6	6319.13	1.00	0.5	27.15	0.001086	1	0	0	0	0
36	0-29	150-375	TP	CMB	0-6	4603.29	0.50	1	57.65	0.002306	1	1	0	0	0
37	30-59	150-375	TP	STM	0-6	3589.67	0.50	0.5	54.55	0.001091	1	0	0	0	0
38	30-59	550-600	TP	CMB	0-6	3225.03	1.00	1	12.14	0.000971	1	0	0	0	0
39	60+	150-375	CP	CMB	0-6	1362.14	0.50	1	82.9	0.003316	1	1	0	0	0
40	60+	150-375	NC	CMB	0-6	746.09	0.50	1	64.86	0.002594	1	1	0	0	0
41	30-59	550-600	TP	CMB	6+	729.67	1.00	1	27.15	0.002172	1	0	1	0	0
42	30-59	550-600	CP	CMB	6+	308.05	1.00	1	72.85	0.005828	1	1	0	0	0
43	0-29	150-375	TP	CMB	6+	291.79	0.50	1	50	0.002000	1	0	1	0	0
44	60+	450-525	CP	CMB	0-6	228.73	0.70	1	90.76	0.005083	1	1	0	0	0
45	0-29	450-525	TP	CMB	0-6	193.85	0.70	1	25.78	0.001444	1	0	0	0	1
46	0-29	450-525	Variable	SAN	Variable	31966.65	0.70	0.8	35.95	0.001611	1	0	0	0	1
47	0-29	150-375	Variable	SAN	Variable	58086.26	0.50	0.8	35.95	0.001150	1	0	0	0	0

Pipe Class	Pipe Age (yrs)	Diameter (mm)	Material	Waste	Cover Depth (m)	Length (m)	Size Weight	Waste Weight	Deficiency Prob. %	Pipe Importance Factor	Applied	Program Years Year 1	Year 2	Year 3	Year 4
48	0-29	150-375	CP	SAN	0-6	50261.23	0.50	0.8	35.95	0.001150	1	0	0	0	0
49	30-59	150-375	Variable	SAN	Variable	73899.92	0.50	0.8	34.27	0.001097	1	0	0	0	0
50	30-59	450-525	Variable	SAN	Variable	47694.55	0.70	0.8	34.27	0.001535	1	0	0	0	1
51	30-59	550-600	Variable	STM	Variable	38331.59	1.00	0.5	34.27	0.001371	1	0	0	0	0.884226562
52	0-29	150-375	Variable	STM	Variable	36686.56	0.50	0.5	35.95	0.000719	1	0	0	0	0
53	0-29	550-600	Variable	SAN	Variable	12179.10	1.00	0.8	35.95	0.002301	1	1	0	0	0
54	30-59	550-600	Variable	SAN	Variable	9215.79	1.00	0.8	34.27	0.002193	1	1	0	0	0
55	0-29	150-375	Variable	CMB	Variable	8486.07	0.50	1	35.95	0.001438	1	0	0	0	1
56	60+	150-375	Variable	SAN	Variable	6450.53	0.50	0.8	59.56	0.001906	1	0	1	0	0
57	30-59	450-525	Variable	STM	Variable	36649.96	0.70	0.5	34.27	0.000960	1	0	0	0	0
58	0-29	450-525	Variable	CMB	Variable	5310.49	0.70	1	35.95	0.002013	1	0	1	0	0
59	30-59	150-375	Variable	CMB	Variable	3852.33	0.50	1	34.27	0.001371	1	0	0	0	0
60	30-59	150-375	Variable	STM	Variable	4503.23	0.50	0.5	34.27	0.000685	1	0	0	0	0
61	0-29	450-525	Variable	STM	Variable	4454.25	0.70	0.5	35.95	0.001007	1	0	0	0	0
62	30-59	450-525	Variable	CMB	Variable	4440.10	0.70	1	34.27	0.001919	1	0	1	0	0
63	60+	150-375	Variable	CMB	6+	3582.02	0.50	1	59.56	0.002382	1	1	0	0	0
64	60+	550-600	Variable	CMB	Variable	3495.87	1.00	1	59.56	0.004765	1	1	0	0	0
65	30-59	550-600	Variable	CMB	Variable	4056.22	1.00	1	34.27	0.002742	1	1	0	0	0
66	0-29	550-600	Variable	STM	6+	2801.87	1.00	0.5	35.95	0.001438	1	0	0	0	1
67	60+	150-375	Variable	STM	Variable	2693.22	0.50	0.5	59.56	0.001191	1	0	0	0	0
68	60+	450-525	TP	CMB	6+	2430.58	0.70	1	59.56	0.003335	1	1	0	0	0
69	0-29	550-600	Variable	CMB	Variable	2350.49	1.00	1	35.95	0.002876	1	1	0	0	0
70	60+	450-525	Variable	STM	Variable	417.58	0.70	0.5	59.56	0.001668	1	0	0	0	1
71	60+	550-600	Variable	STM	Variable	281.63	1.00	0.5	59.56	0.002382	1	1	0	0	0
72	60+	450-525	TP	SAN	Variable	267.61	0.70	0.8	59.56	0.002668	1	1	0	0	0
73	60+	550-600	TP	SAN	6+	98.54	1.00	0.8	59.56	0.003812	1	1	0	0	0
74	30-59	150-375	Variable	SAN	Variable	3632.78	0.50	0.8	34.27	0.001097	1	0	0	0	0
75	0-29	150-375	Variable	SAN	Variable	5642.94	0.50	0.8	35.95	0.001150	1	0	0	0	0
76	30-59	450-525	Variable	SAN	Variable	987.09	0.70	0.8	34.27	0.001535	1	0	0	0	1
77	30-59	150-375	Variable	CMB	0-6	646.07	0.50	1	34.27	0.001371	1	0	0	0	0
78	0-29	150-375	Variable	STM	0-6	623.04	0.50	0.5	35.95	0.000719	1	0	0	0	0
79	0-29	150-375	NC	CMB	Variable	443.77	0.50	1	35.95	0.001438	1	0	0	0	1
80	30-59	150-375	Variable	STM	0-6	402.24	0.50	0.5	34.27	0.000685	1	0	0	0	0
81	0-29	450-525	Variable	STM	Variable	160.01	0.70	0.5	35.95	0.001007	1	0	0	0	0
82	60+	150-375	Variable	CMB	Variable	151.64	0.50	1	59.56	0.002382	1	1	0	0	0
83	0-29	450-525	PEP	SAN	0-6	149.04	0.70	0.8	35.95	0.001611	1	0	0	0	1
84	60+	450-525	NC	CMB	0-6	94.81	0.70	1	59.56	0.003335	1	1	0	0	0
85	0-29	550-600	Variable	STM	0-6	66.91	1.00	0.5	35.95	0.001438	1	0	0	0	1
86	30-59	450-525	NC	CMB	0-6	54.00	0.70	1	34.27	0.001919	1	0	1	0	0
87	30-59	550-600	NC	CMB	0-6	52.12	1.00	1	34.27	0.002742	1	1	0	0	0
88	60+	550-600	NC	CMB	0-6	48.77	1.00	1	59.56	0.004765	1	1	0	0	0
89	30-59	450-525	CMP	STM	0-6	6.10	0.70	0.5	34.27	0.000960	1	0	0	0	0

Annual Inspection (m)	220,000.00	220,000.00	220,000.00	220,000.00
Annual Inspection Contraint (m)	220,000.00	220,000.00	220,000.00	220,000.00

Pipe Class	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12
1	0	0	0	0	0.761804339	0.238195661	0	0
2	0	0	0	1	0	0	0	0
3	0	0	0	0	0	1	0	0
4	0	0	0	0	1	0	0	0
5	0	0	0	0	1	0	0	0
6	0	0	0	0.685814526	0.314185474	0	0	0
7	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0
11	0	0.687517336	0.312482664	0	0	0	0	0
12	0	0	1	0	0	0	0	0
13	0	0	1	0	0	0	0	0
14	0	0	0	0	0	1	0	0
15	0	0	0	0	0	0.09930002	0.90069998	0
16	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0
20	1	0	0	0	0	0	0	0
21	0	1	0	0	0	0	0	0
22	1	0	0	0	0	0	0	0
23	0	0	0	0	0	0	1	0
24	0	0	0	0	0	0	1	0
25	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	1
27	0	0	0	0	0	0	0.093353583	0.906646417
28	0	0	0	0	0	0	0	0
29	0	0	0.521174385	0.478825615	0	0	0	0
30	0	0	0	1	0	0	0	0
31	0	0	0	0	0	0	0	0
32	0	0	0	0	0	0	0	0
33	0	0	0	0	0	0	1	0
34	0	0	0	0	0	0	0	0
35	0	0	1	0	0	0	0	0
36	0	0	0	0	0	0	0	0
37	0	0	1	0	0	0	0	0
38	0	0	0	1	0	0	0	0
39	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0	0
41	0	0	0	0	0	0	0	0
42	0	0	0	0	0	0	0	0
43	0	0	0	0	0	0	0	0
44	0	0	0	0	0	0	0	0
45	0	0	0	0	0	0	0	0
46	0	0	0	0	0	0	0	0
47	1	0	0	0	0	0	0	0

Pipe Class	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12
48	0.17075388	0.82924612	0	0	0	0	0	0
49	0	1	0	0	0	0	0	0
50	0	0	0	0	0	0	0	0
51	0.115773438	0	0	0	0	0	0	0
52	0	0	0	0	0	1	0	0
53	0	0	0	0	0	0	0	0
54	0	0	0	0	0	0	0	0
55	0	0	0	0	0	0	0	0
56	0	0	0	0	0	0	0	0
57	0	0	0	1	0	0	0	0
58	0	0	0	0	0	0	0	0
59	1	0	0	0	0	0	0	0
60	0	0	0	0	0	1	0	0
61	0	0	0	1	0	0	0	0
62	0	0	0	0	0	0	0	0
63	0	0	0	0	0	0	0	0
64	0	0	0	0	0	0	0	0
65	0	0	0	0	0	0	0	0
66	0	0	0	0	0	0	0	0
67	1	0	0	0	0	0	0	0
68	0	0	0	0	0	0	0	0
69	0	0	0	0	0	0	0	0
70	0	0	0	0	0	0	0	0
71	0	0	0	0	0	0	0	0
72	0	0	0	0	0	0	0	0
73	0	0	0	0	0	0	0	0
74	0	1	0	0	0	0	0	0
75	0	1	0	0	0	0	0	0
76	0	0	0	0	0	0	0	0
77	1	0	0	0	0	0	0	0
78	0	0	0	0	0	1	0	0
79	0	0	0	0	0	0	0	0
80	0	0	0	0	0	1	0	0
81	0	0	0	1	0	0	0	0
82	0	0	0	0	0	0	0	0
83	0	0	0	0	0	0	0	0
84	0	0	0	0	0	0	0	0
85	0	0	0	0	0	0	0	0
86	0	0	0	0	0	0	0	0
87	0	0	0	0	0	0	0	0
88	0	0	0	0	0	0	0	0
89	0	0	0	1	0	0	0	0
	220,000.00	220,000.00	220,000.00	220,000.00	220,000.00	220,000.00	220,000.00	90,101.37
	220,000.00	220,000.00	220,000.00	220,000.00	220,000.00	220,000.00	220,000.00	220,000.00