University of Southern Queensland
Faculty of Engineering and Surveying

Developing a Model to Predict Water Main Failures

A dissertation submitted by
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EXECUTIVE SUMMARY

Many water authorities own water mains that date to the beginning of the last century. As these assets begin to reach the end of their useful lives, failures are becoming increasingly more common. With only limited financial resources available, water authorities are faced with the challenge of whether to repair or replace damaged water mains. A useful decision making tool in this area is a water main failure prediction model.

ActewAGL is a water utility operating and maintaining the water supply network in the ACT for the asset owner Actew Corporation. The network consists of in excess of 3000 kilometres of water mains and services approximately 360,000 customers. Although not currently considered a problem, the water main failure rate in the ACT appears to be on the rise. Therefore, Actew recognizes the need to better understand the causes of water main failures and to be proactive in developing policies to most efficiently deal with the effects of failure.

The objective of this study was to investigate the methods, parameters and theory used in existing water main failure models and to use these findings to develop a customised water main failure prediction model taking into account limitations with the type and quality of water main failure data available.

Research showed that the key factors influencing the structural performance of buried pipes are the pipe characteristics, soil embedment conditions and the internal/external loadings on the buried pipe. Any significant impacts on these factors can lead to failure. Water main failure prediction models endeavour to use this knowledge to predict the likelihood of or time until failure.

The ultimate in water main failure prediction models was shown to be a physically based model that predicts time to failure for an individual water main based on the actual pipe condition and local environmental influences. However, difficulties and costs associated with obtaining input data for a physical model has resulted in the popularity of a more cost effective statistical failure prediction model which attempts to identify trends in past performance data and assumes that these will continue on into the future.

Analysis of historical water main failure data in the ACT identified a number of data limitations including missing or incomplete data and a lack of the necessary data to develop a physical model. Most failures in the ACT were shown to occur in small diameter cast iron water mains during the winter period or low rainfall periods. The occurrence of these failures was attributed to soil moisture or frost loads and temperature differentials caused by low ground temperatures.

Although it was clear that a physical water main failure prediction model would be ideal for the ACT, data and resource limitations meant that a statistical failure prediction model was considered most appropriate. Two multivariate failure prediction models (see Figures 1 and 2) were proposed using multiple regression techniques with the dependent variable being total number of failures and the explanatory variables time (month for Model 1 and year for Model 2) and rainfall (12 month totals - mm). Ground temperatures were also considered for the models. However, analysis showed that its inclusion did not significantly improve the models accuracy due to its high correlation with rainfall.

Further testing and validation of the models is required. However, preliminary analysis showed promising results with Model 1 and Model 2 obtaining coefficients of multiple determination of 78% and 76% respectively. Residual analysis identified possible concerns with autocorrelation occurring suggesting there is scope for improvement in the model. This would also include investigating the possibility of adding more explanatory variables to the model.

RECOMMENDATIONS

As a result of this study a number of recommendations were made for further work in order to improve Actew's ability to monitor system performance and predict water main failures. These are as follows.

- Compile historical failure records into a central water main failure database and add links to the GIS and asset management systems.
- Incorporate physical parameters into water main failure data collection processes.
- Conduct further testing, validation and improvement of the multivariate statistical models developed in this study.
- Conduct preliminary investigations into the development of a physically based water main failure prediction model.

Figure 1 - Equation for Model 1

Total Number of Failures $= 123.997 + 237.33e^{0.0025X_1} - 0.175X_2$

where x_1 = time (month)

x_2 = rainfall (mm)

Figure 2 - Equation for Model 2

Total Number of Failures $= 145.259 + 241.68e^{0.0304X_1} - 0.206X_2$

where x_1 = time (year)

x_2 = rainfall (mm)

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Date

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CHAPTER 1

INTRODUCTION

1. Introduction

1.1. Outline of the Study

In recent years much has been said about the importance of taking steps to ensure water supply sustainability for future generations. With most attention being focussed on securing additional supply options, an important aspect often overlooked is the maintenance, replacement and renewal of existing water supply networks. This too is an important consideration in ensuring water supply needs remain sustainable.

Water authorities in Australia have made large investments in water infrastructure. According to the report 'Time Running Out: Shaping Regional Australia's Future' (2000) the total replacement costs of water infrastructure assets in Australia is estimated at being in excess of $90 billion. Water supply network assets make up a significant proportion of this replacement cost.

Many water supply networks date from early last century and are beginning to show signs of deterioration. A major challenge facing the owners of these networks is the problem of how best to cope with aging infrastructure. Engineers Australia (2005) in the Australian Infrastructure Report Card reported that spending on water asset renewals is not enough to keep up with the rate of deterioration. As network assets begin to reach the end of their useful lives the frequency of network failures appears to be on the increase. This makes it increasingly more difficult to meet legislative requirements and customer service standards.

The Water Service Association of Australia (WSAA) identifies water main failures as a key indicator of the performance of a water supply network. Water main failures result in large financial and social costs to both the water authority and the wider community. Typical financial costs include costs of repairing or replacing damaged assets, restoration of the damaged environment and compensation for damaged property. Social costs include increased rates and taxes, environmental damage, loss of reputation, public inconvenience and the perceived waste of a precious resource at time of drought and water restrictions.

With only limited financial resources available to operate and maintain water supply pipe networks, it is critical that these are spent wisely and efficiently. This means it is important to be able to analyse how a network is currently performing, identify potential areas of risk and predict likely future performance in order to determine when a water main should be repaired or when it should be replaced. This will lead to better, more informed decisions regarding water main renewal, replacement and maintenance strategies. A useful tool in predicting future performance is a water main failure prediction model.

The purpose of this project is to investigate the structural design of buried pipes, common water main failure modes and existing water main failure prediction models and to develop a customised water main failure prediction model based on these findings.

1.2. Background

ActewAGL is a multi-utility providing electricity, gas, water and waste-water services to the Australian Capital Territory (ACT) and surrounding areas. ActewAGL operates and maintains the water supply network for the asset owner Actew Corporation.

The ACT water supply network services an estimated 360,000 customers and consists of more than 3000 kilometres of water mains. The first reticulation mains in the ACT date back to approximately 1915. However, the majority of the network has been constructed since the 1960's when rapid growth was experienced in the ACT.

According to the Actew Corporation Asset Management Plan (2007) water main failures in the ACT are below the Australian industry average and do not currently pose a significant problem. Analysis, however, has shown that the overall rate of water main failures has been increasing gradually and is likely to become a problem in the future.

Due to the relatively low water main failure rates, Actew's current primary maintenance strategy is to run water mains to failure. Water main replacement programs have also been implemented to replace asbestos cement (AC) mains and other sections of main that experience relatively high rates of failure.

Despite the current relatively low overall water main failure rate, it is recognised that an aging network, increasing failure rate and more stringent service level agreements and environmental requirements will ultimately result in maintenance strategies needing to become more proactive in identifying mains that pose a potential failure risk and taking steps to prevent failure or to replace the mains before they become a significant problem.

Actew is looking at taking steps to improve the quality of water main failure data recorded in order to carry out further analysis of failure trends. Failure analysis conducted so far has been used to develop asset management plans and water main replacement programs.

The aim of this project is to build upon existing water main failure analysis and to develop a model that can be used to analyse system performance trends and assist in the water main replacement decision making process.

1.3. Research Objectives

The objectives of this research project are to:

1. Investigate the structural design of buried pipes to identify the factors that determine how a buried pipe performs in service.
2. Investigate common water failure modes and their causes.
3. Critically evaluate existing water main failure prediction models.
4. Analyse the performance of Actew's distribution/reticulation system in relation to water main failures using findings in Objectives 1 and 2.
5. Develop a customised water main failure prediction model based on the analysis of Actew performance data in Objective 4.

The project specification is included in Appendix A.

In order to reach these objectives the research will be conducted in three stages.

The first stage of the project will be carried out in the form of a literature review covering the first three objectives. The purpose of this is to gain an understanding of the scope of works already relating to the topic. Information sources include textbooks, journal articles, conference proceedings, international standards and design manuals. Findings from the literature review will be used in the remainder of the project.

The second stage of the project relates to objective four. This will involve firstly compiling and reviewing Actew water main failure data to determine data quality and quantity and to identify limitations in the available data. Secondly this compiled data set will be analysed using the parameters identified in the literature review. Findings of the review will determine model type and parameters to be used in the model.

The third stage of the project is the development of a customised water main failure model. The model developed will be the one deemed the most appropriate taking into account resource and data limitations.

1.4. Scope of the Project

The scope of this project involves looking at current practice on the topic of water main failure prediction and using this knowledge to develop a customised failure prediction model. It is recognised that many years of research has gone into developing some of the existing failure prediction models and fully developing a customised model is a long term project beyond the scope of this study. It is not the intent to develop a model that could be considered best practice in this field, but rather to lay the foundations for a customised model taking into account current data and resource limitations. Marked improvements would be required before a best practice model could be considered.

1.5. Dissertation Overview

This dissertation has been divided into seven chapters as outlined below.

<u>Chapter 1 – Introduction</u>

Chapter 1 provides an introduction to the research project that has been conducted. Details covered in the chapter include the importance of this topic, background into the specific need of this study, research objectives, scope of the project and a brief dissertation overview.

Chapter 2 – Literature Review

Chapter 2 is a comprehensive review of literature relating to water mains and water main failure prediction models. The review has focussed on three main areas – the structural performance of buried pipes, the causes and types of water main failures and existing water main failure prediction models.

Chapter 3 – Methodology

Chapter 3 outlines the methodology used in the study to develop the customised water main failure prediction model. More specifically it details the methods used to analyse existing water main failure data in the ACT and provides the background to regression analysis which was used to develop the models in Chapter 5.

Chapter 4 – Actew Water Main Failure Data Analysis

Chapter 4 details the data analysis conducted on historical water main failure data in the ACT. The analysis concentrated on identifying general, spatial and temporal trends and patterns in the data and findings influenced the type of failure prediction model proposed in Chapter 5.

Chapter 5 – Customised Water Main Failure Prediction Model

Chapter 5 details the development of the two customised water main failure prediction models. The chapter also outlines some of the analysis carried out to assess the quality of the model and discusses the significance of any findings.

Chapter 6 – Comparison of Proposed Models with Existing Failure Prediction Models

Chapter 6 acknowledges some of the difficulties in comparing different types of water main failure prediction models. It then compares the proposed models to existing failure prediction models by looking at the different uses of models, model input variables, model output and model accuracy.

Chapter 7 – Conclusion and Recommendations

Chapter 7 summarises the outcome of the study and how well the research objectives were able to be met. It describes some of the positives that have come out of the project and some of the areas that still need further investigation. The chapter concludes by making some recommendations for further works.

CHAPTER 2

LITERATURE REVIEW

2. Literature Review

2.1. Introduction

A wide variety of literature has been published on the subject of water main failures. The aim of the literature review is to analyse this available literature with a view to finding information applicable to Actew's water supply network that will be useful in developing a customised water main failure prediction model.

Material for the literature review was obtained from a variety of sources including textbooks, papers published by researchers and research institutions, technical groups, technical libraries, international standards and online resources

The scope of the literature review covers three main areas – buried pipe design, water main failures and water main failure prediction models.

2.2. Buried Pipe Design

An overview of the theory of buried pipe design is included to highlight the factors that are critical in the performance of a water main in service and thus have a bearing on water main failures.

2.2.1. Development of Design Procedure

According to Watkins and Anderson (2000) the need for detailed design procedures for buried pipes was identified in the 1920's. Prior to this, design was mostly empirical. The purpose of detailed design procedures was to prevent water main failures that were quite common at the time but also to ensure overdesign did not occur.

Pioneering work in the development of buried pipe design standards was carried out by Marston, Spangler and Watkins. Marston (1929) proposed a theory for predicting soil loads on buried rigid pipes. He reasoned that pipe failures could be avoided by ensuring that the soil loads acting on the buried pipe were less than the failure strength of the buried pipe allowing for a factor of safety.

Spangler (1941) discovered that flexible pipes, new to the market at the time, performed differently in situ to rigid pipes and that pipe deflection and embedment soil stiffness play an important role in the structural performance of buried flexible pipes. Experimentation showed that excessive deflection had an adverse effect on pipe performance, so Spangler sought to limit pipe deflection below 5%. In order to predict the deflection of buried flexible pipes Spangler developed the Iowa Formula which is based on Marston soil loads, pipe ring stiffness and the stiffness of the embedment soil.

The soil parameters in Spangler's formula were determined empirically and did not give reliable results in all cases. To overcome this problem Watkins (1958) modified the Iowa formula introducing a modulus of soil reaction which is a function of depth of soil cover and pipe ring stiffness.

The work of Marston, Spangler and Watkins forms the basis of buried pipe design today. Others also have made a contribution to design procedures by proposing modifications to existing methods to improve accuracy and correct deficiencies. As the complexity of the structural performance of buried pipes has become better understood, additional factors have been included in pipe design procedures including hydrostatic loads, superimposed surface loads, circumferential wall strain and ring buckling.

Alternative design methods of varying levels of complexity and accuracy have been proposed and some of these used in design procedures. However, the level of complexity involved in some methods is questionable due to the intrinsic variability of parameters used in the analysis, for example soil parameters. Also, it is not always easy to validate these designs in the field. Despite some of the different methods used to calculate parameters, design procedures follow the same basic processes.

2.2.2. Factors in the Structural Performance of Buried Pipes

In order to understand the structural performance of buried pipes it is first necessary to distinguish between rigid (cast iron) and flexible (ductile iron and PVC) pipes which differ in the way they resist loads.

A technical note by Vinidex (2000) explains the difference between rigid and flexible pipe. Rigid pipes carry loads by transferring the load from the top of the pipe, through the pipe wall to the bedding. The imposed load is, therefore, concentrated over a small area at the base of the pipe and a high wall thickness is required.

On the other hand, flexible pipes resist load by transferring the load from the top of the pipe to the bottom and side support of the trench. The mechanism that causes load transfer is vertical deflection of the pipe under load which results in horizontal deflection of the pipe into the side support of the trench.

Flexible pipes are more efficient than rigid pipes because they can shed load over a larger area by deforming without causing structural damage. This means wall thicknesses can be reduced for the same carrying capacity. Figure 2.1 illustrates the difference in soil loads acting on rigid and flexible pipes.

The improved qualities of flexible pipe have lead to the superseding of cast iron as a material in water supply construction. Despite this, the structural performance of cast iron pipes is still relevant as it remains the dominant material in most pipe networks.

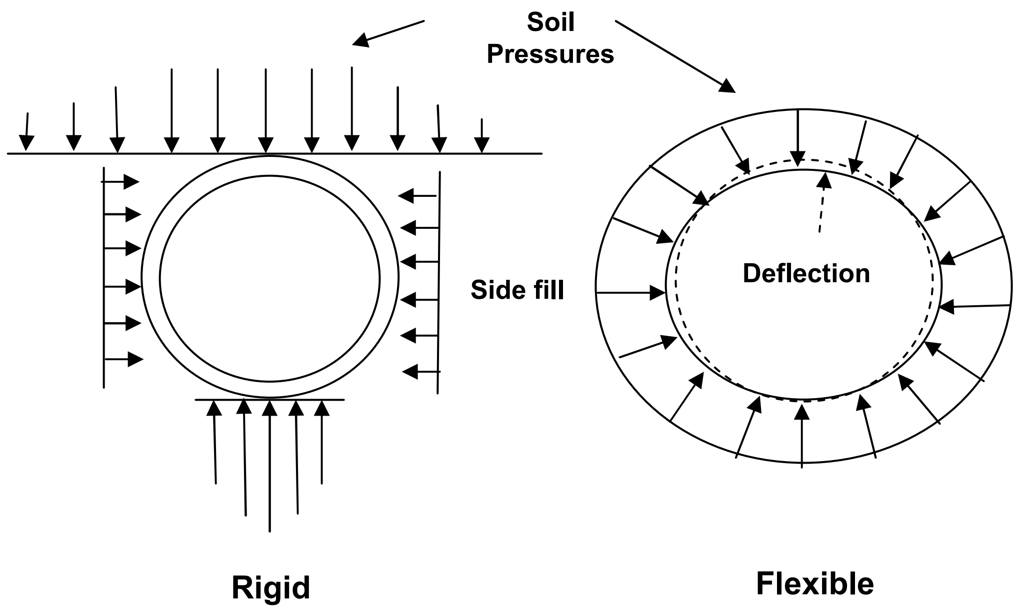

Figure 2.1 Comparison of Soil Pressures against Rigid and Flexible Pipes

<u>Rigid Pipes</u>

With the integration of ductile iron and PVC into water supply construction practices, the original design methods for cast iron pipe are now obsolete or superseded and difficult to obtain. However, Rajani and Makar (2000) and Makar et al (2000) outline basic design procedures and discuss relevant factors in the structural performance of cast iron pipes that original design methods overlook.

According to these two studies, cast iron pipe design methods originally only recognised the effects of known earth loads and internal pressures on the performance of a cast iron pipe and thus used these to determine the required pipe wall thickness. Subsequent studies have shown other factors that affect the structural performance of buried cast iron pipes include corrosion pitting which reduces pipe wall thickness and induced loads due to differential soil movement, thermal effects and frost load effects.

Flexible Pipes

In Australia the standard applicable for the structural design of buried flexible pipelines is AS/NZS 2566.1:1998 Buried Flexible Pipelines – Part 1: Structural Design.

AS/NZS 2566.1:1998 shows that that the structural performance of a buried flexible pipe is dependent on three main factors a) pipe characteristics, b) soil embedment characteristics and c) the magnitude of internal and external loadings. If these three factors are kept within acceptable limits successful design is possible.

Pipe Characteristics

Pipe characteristics determine how a pipe performs in service when subjected to internal operating pressures and imposed loads. Therefore, pipe selection must match the intended function of the pipe without reaching its performance limits which are pipe failure (collapse, bursting, and fracture) and/or excessive pipe deformation as defined by Watkins and Anderson (2000).

Important pipe characteristics for design purposes are pressure rating, pipe wall thickness and pipe ring stiffness. Pressure ratings determine a pipeline's maximum allowable operating pressure, pipe strength is a function of the pipe wall thickness and pipe ring stiffness is important in resisting deflections.

Other important factors that affect pipe durability and performance include the pipe manufacturing process, pipe tolerances and pipe coatings and linings. The pipe manufacturing process can introduce pipe defects due to metal inclusions, incorrect rate of cooling or dimensions outside tolerance such as minimum wall thickness. Defects in pipe coatings or linings can lead to an increased risk of corrosion. Figure 2.2 illustrates important pipe characteristics used in design.

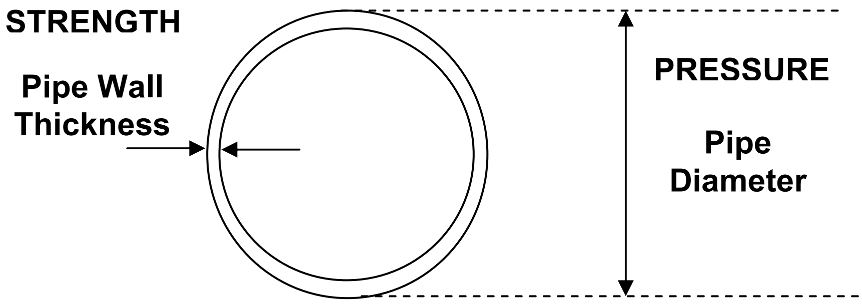

Figure 2.2 Important Characteristics of a Buried Pipe

Soil Embedment Characteristics

Soil embedment characteristics are important in the performance of buried flexible pipes. Factors that must be controlled in buried pipe design include embedment geometry, embedment materials, compaction and soil moduli. Figure 2.3 illustrates key pipe installation terminology.

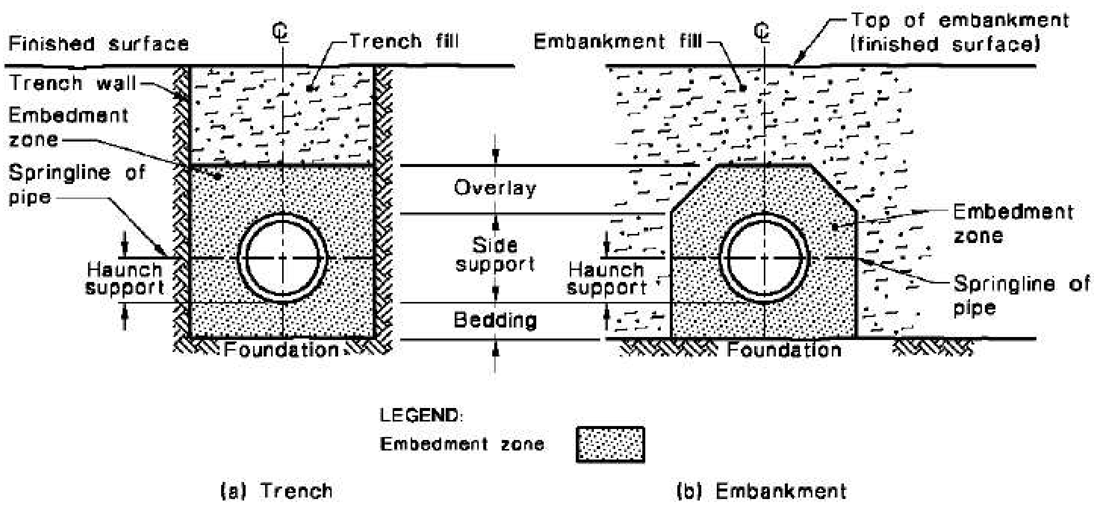

Figure 2.3 Buried Flexible Pipe Installation Terminology (AS/NZS 2566.1:1998)

Embedment geometry is shown in Figure 2.4 and includes embedment width, depths of bedding and overlay and minimum cover. These need to be controlled because they can affect the magnitude of loads imposed on the buried pipe.

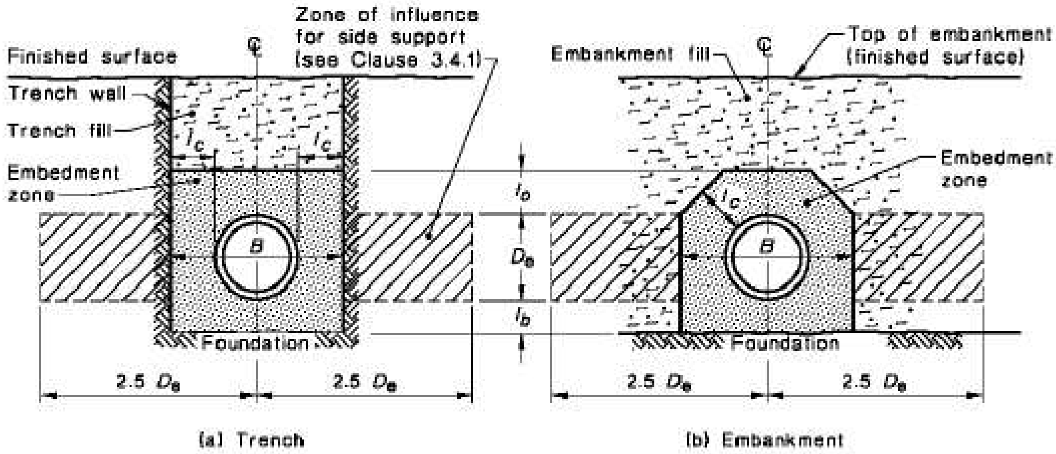

Figure 2.4 Embedment Geometry (AS/NZS 2566.1:1998)

Embedment materials must be free of organics and corrosive materials and meet strict specifications. This is to prevent differential soil settlement that may impart stresses on the pipe, chemical attack of the pipe coating and to promote effective soil compaction.

Careful compaction must be undertaken to achieve optimum soil density and uniform compaction. If this does not occur then it can result in pipe damage.

Pipe deflection is a function of the soil moduli or stiffness. Soil stiffness is determined from the modulus of native soil and embedment soil. If pipe must be laid in poor quality soil then it is important to select embedment soil to achieve adequate soil stiffness to resist deflection.

Internal and External Loadings

The structural performance of buried pipes is influenced by the magnitude of internal and external loads imposed on the buried pipe. To perform successfully a buried pipe must be able to safely resist imposed loads with a sufficient margin of safety.

Loads taken into account for design include trench or embankment fill, external hydrostatic loads, superimposed dead and live loads and the mass of the contents of the pipe. Figure 2.5 illustrates the effects of a superimposed live surface load due to traffic. Successful design requires that all loads are accurately predicted with a sufficient margin of safety.

The factors discussed above help to understand the structural performance of buried pipes and form the basis for design procedures.

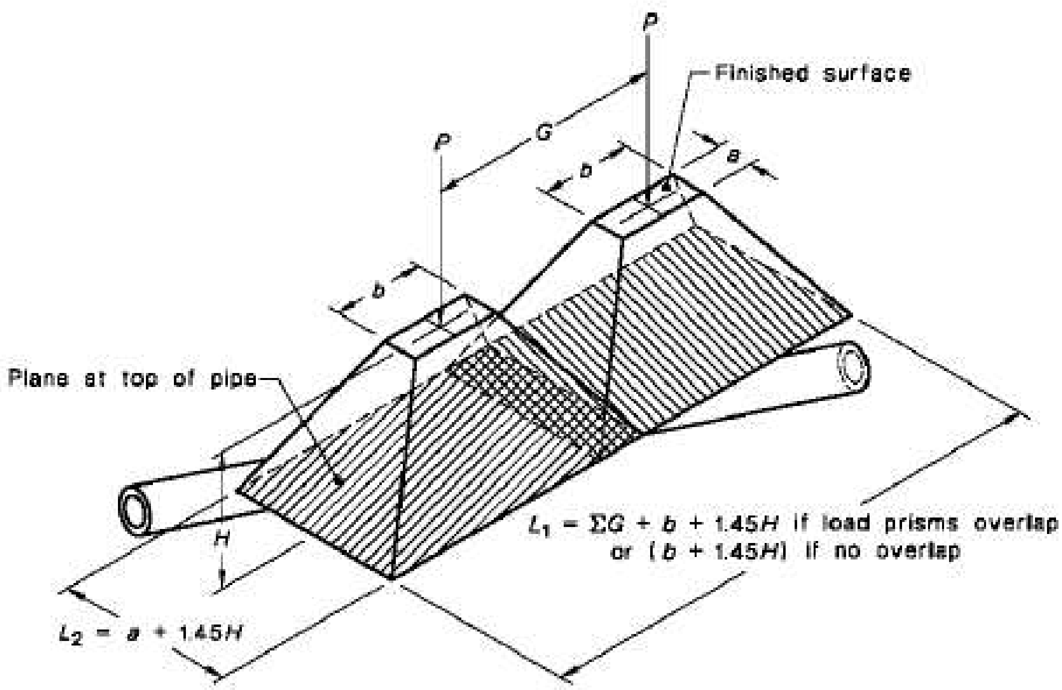

Figure 2.5 Traffic Load Effects (AS/NZS 2566.1:1998)

2.2.3. AS/NZS 2566.1:1998 Design Procedure

The design criteria for AS/NZS 2566 is explained in the commentary to the standard published by Standards Australia (1998) and described as the adoption of rationally based design equations that are expressed as simply as possible while still yielding acceptably accurate predictions. Some feel that the application of the design standard results in a conservative design.

AS/NZS 2566.1:1998 shows that the structural performance of a buried flexible pipe depends on the pipe characteristics, soil stiffness and the type and magnitude of internal and external loadings. To achieve a satisfactory design a designer may need to vary one or more of these parameters.

A satisfactory design involves selecting a pipe-soil system that will safely meet strength and deflection requirements. To assist in this the design standard provides design equations for predicting design loads and the critical pipe ring performance criteria of vertical deflection, strength and buckling. These equations are based on a design life, or long term basis, of 50 years. The actual service life of a buried flexible pipe can be expected to exceed 50 years.

2.2.4. Summary

A review of literature relating to buried pipe design has been conducted to highlight the critical factors in buried pipe design. Generally design procedures are in agreement. Some have proposed more accurate and complex design procedures, however the increased complexity is questionable due to the inherent variability of some of the design parameters.

The three most important considerations in buried pipe design are the pipe, the embedment conditions and the pipe loadings. The job of the designer is to select the pipe-soil interaction that can safely resist the design loads.

Loads cannot always be accurately predicted and are prone to change over time due to changed embedment conditions. This means that some pipe failures are inevitable.

As more research is carried out into how buried pipes perform in service it is likely that more accurate design methods will be adopted in the future. Until these new methods are validated against actual field data the existing simplified design methods will continue to be used.

2.3. Water Main Failures

An overview of why and how water mains fail can aid in understanding the methods and parameters used in water main failure modelling.

Most of the literature regarding water main failure modes and failure mechanisms is relatively recent. This is because increasing numbers of water mains are beginning to reach the end of their useful lives and water authorities are looking to understand the complex processes that lead to failures so they can learn how to best cope with them.

2.3.1. What is a Water Main Failure?

The Dictionary of Civil Engineering (2008) defines a failure as 'a condition at which a structure meets a limit state. It may be due to leakage, deflection or cracking, but it usually does not involve rupture because most structures are considered to be unsafe, therefore unusable, before they collapse.'

Water Services Association of Australia (WSAA) defines a water main break or failure as a break, leak or burst in any potable or reuse water main and includes failure of fittings such as hydrants, valves, tapping points and pipe joints. This definition was developed to provide an indication of overall network performance and frequency of customer disruption.

This research project is focussed primarily on the performance of potable water mains in service and thus failures in reuse mains, hydrants and valves will be excluded from the study.

2.3.2. Why do Water Mains Fail?

The mechanisms that lead to water main failures are complex and have only recently begun to be understood. Water main failures can generally be attributed to one or more of the following causes.

Manufacturing Defects/Limitations

Makar et al (2001) and Nicholas and Moore (2007) describe typical pipe defects or flaws resulting from poor quality control in manufacturing. These include uneven pipe wall thicknesses, porosity and impurities. Manufacturing defects are points of weakness that could potentially initiate cracks or other problems. Also pipe characteristics are influenced by the method of manufacture. For example, cast iron pipes manufactured using the 'Super De Levaud' have reduces corrosion resistance compared to sand cast pipes.

Human Error

Water mains are prone to fail because of human influences. Makar et al (2001) lists a number of human errors that could potentially lead to water main failures. These include design errors, poor handling or installation techniques, third party damage and poor repair techniques. Design errors can lead to failure due to excess pressures or loads. Poor handling or installation techniques can damage pipe and lead to additional forces being induced upon the buried pipe. Third party damage may be caused by excavation without accurate utility clearances, superimposed surface loads due to construction equipment or construction directly over a water main. Previous repairs may become a weak point in a pipeline which could ultimately lead to failure.

Corrosion

It was once thought that corrosion was the sole cause of a number of water main failures. Studies have now shown that in many failures corrosion weakens the pipe but other mechanisms such as internal pressures can actually cause the failure. Makar (2000), Makar et al (2001) and Nicholas and Moore (2007) identify two types of corrosion for iron pipes – pitting that reduces the pipe wall thickness and graphitisation where iron is leached from the pipe leaving a weaker matrix of graphite flakes. The overall effect is to reduce pipe wall thickness and thus pipe strength. The CSIRO (2007) and Hu and Hubble (2007) show that corrosion can be a problem with PVC and asbestos cement water mains also. Figure 2.6 shows an illustration of the conditions leading to corrosion reproduced from the study by Makar et al (2001). These include corrosive soils, differential aeration, dissimilar metals and stray currents.

Excess Internal Pressures

Pipeline design typically includes allowances for pressure surges associated with normal pipeline operation. However, pressure transients due to malfunctioning equipment or pumping against a closed valve can cause water mains to fail due to bursting or blow out.

Changed Soil Embedment Conditions

Soil embedment conditions can change due to a number of causes including expansive soils, voids or hard spots in bedding materials due to water leaks or differential ground movement, groundwater movement and reduced soil cover. The effect of these changes is increased loading on buried pipes which can lead to failure.

Thermal Effects

Many studies have acknowledged the effects a change in water and ground temperature can have on water main failures. For example, Habibian (1993) associated the development of tensile forces on a restrained pipe with the contraction of pipe materials from a large drop in water temperature flowing through a pipe. Habibian further discussed the effects of differential loading due to temperature differences on the inside and outside of a pipe and increased external loading due to frost loads. McNeill and Edwards (2002) also highlighted the increased corrosion rate caused by a drop in temperature in winter.

Material Fatigue/Deterioration

All materials are subject to fatigue from prolonged loading as well as deterioration over time. Due to the long service life of a water main, fatigue and deterioration can reduce a pipes ability to resist imposed loads to a level where they are susceptible to failure.

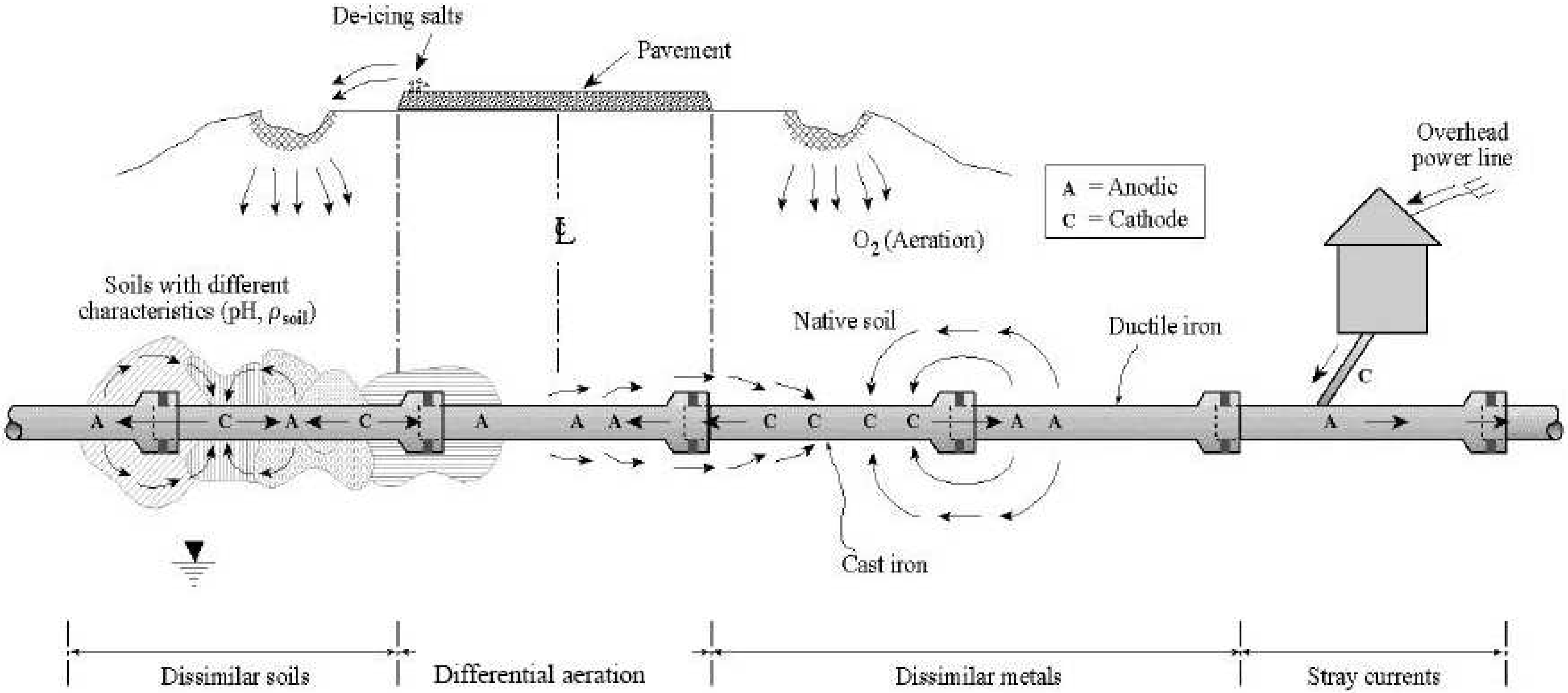

Figure 2.6 – Conditions Leading to Corrosion (Rajani and Kleiner 1999)

2.3.3. Water Main Failure Modes

Published literature is generally in agreement regarding the typical modes of water main failures although some differences exist according to different material types. Rajani and Kleiner (1999) described four main failure modes – referring to three failure modes (circumferential, longitudinal and split bell) as classified by O'Day et al (1986) and added to this pinholes. An illustration of the failure modes reproduced from this study is shown in Figure 2.7. Makar et al (2000) observed similar failure modes in grey cast iron water mains as well as bell shearing and spiral cracking. Hu and Hubble (2007) confirmed similar failure modes for asbestos cement water mains.

Recent studies have been conducted by NCRC (1995), the UK Water Industry Research (2002) and WSAA (2003) with the aim of analysing regional water main failure data to develop a database of common water main failure modes. The findings of these studies show that the failure modes described previously accurately reflect actual pipe performance in the field. The type of failure mode is a function of the pipe type (rigid or flexible) and the pipe material.

WSAA (2003) published a table defining common failure modes in pressurised pipeline systems applicable to Australian pipes, environments and operating conditions. This is reproduced in Figure 2.8. In addition to the failure modes described earlier WSAA also lists perforation, pipe wall rupture/tear, tapping failures and third-party damage. These failure mode descriptions have been adopted by Actew.

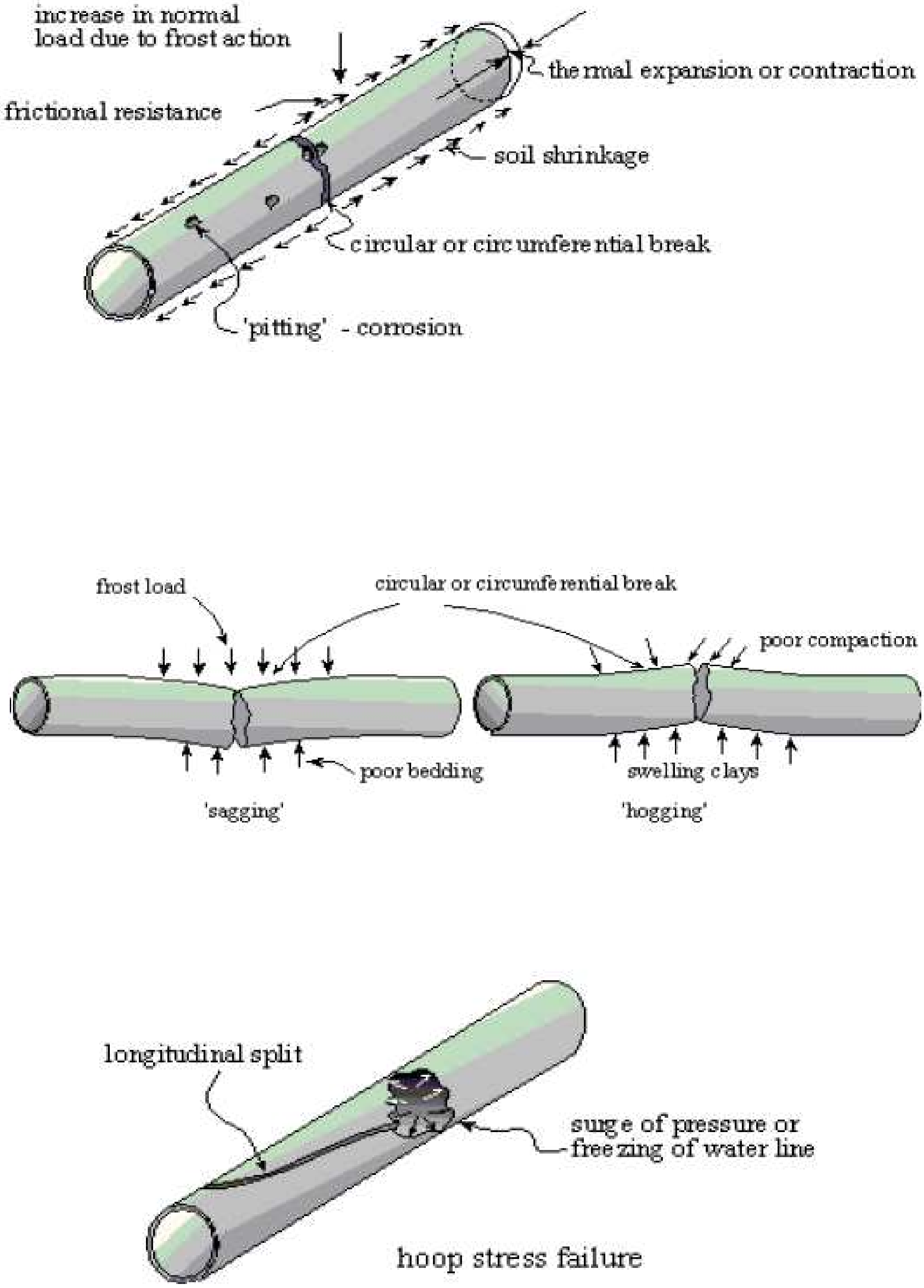

Figure 2.7 – Failure Modes for Buried Pipes (Rajani and Kleiner 1999)

WATER SERVICES ASSOCIATION
of Australia

COMMON FAILURE MODES IN PRESSURISED PIPELINE SYSTEMS

The following tables summarise the most common types of field failure modes in water supply mains and pressure sewers and associated fittings and appurtenances. The table has been developed specifically for Australian pipes, environments and operating conditions and is designed standardise the reporting of field data for entry into Water Agency failure databases.

Failure Mode	SCL	DICL	PVC	PE	CICL	AC	GRP	Copper	Comments
PIPES									
Piece blown Out		✓	✓	✓	✓	✓	✓		➢ Common in cast iron pipes
Perforation	✓	✓	✓	✓	✓			✓	➢ Perforations in PVC and PE pipe are usually small splits
Broken back (Circumferential break)					✓	✓		✓	➢ Common in cast iron pipes
Longitudinal split			✓		✓	✓			➢ Longitudinal fractures are also possible in PE pipe but are very uncommon
Pipe wall rupture/tear	✓						✓	✓	➢ Ductile pipe wall ruptures are also possible in DICL pipe but are very uncommon
Associated with or during tapping		✓	✓						➢ DICL pipelines experienced localised corrosion adjacent to uninsulated copper property service connection points ➢ PVC-U pipelines have experienced failures during tapping operations under pressure where the pipe fractures from the tapped hole
Leaking joint	✓	✓	✓	✓	✓	✓	✓	✓	➢ Pipelines with non-elastomeric seal joints e.g. lead, lead compound are more likely to experience joint leaks. Flange gaskets are also prone to leakage especially at higher operating pressures
Third-party damage	✓	✓	✓	✓	✓	✓	✓	✓	Third party damage should not be considered a pipe failure as such.

Figure 2.8 – Common Water Main Failure Modes for Australian Conditions

2.3.4. Failure Mechanisms

Water mains typically fail according to one of the failure types discussed previously. A number of possible failure mechanisms have been proposed to describe why each of these failure types occurs and are outlined below.

<u>Circumferential Breaks</u>

Circumferential breaks are breaks around the circumference of the pipe wall and are caused by longitudinal stresses. Figure 2.9 illustrates a circumferential break in a cast iron pipe and Figure 2.7 the mechanisms leading to circumferential breaks.

Rajani and Kleiner (1999) attribute the causes of circumferential breaks to thermal contraction acting on a restrained pipe, bending stresses due to soil differential movement or large voids in the bedding near the pipe, inadequate trench and bedding practices and third party interference. Rajani and Makar (2000) and Makar et al (2001) also discuss the contribution of corrosion to circumferential failures and refer to a spiral cracking type failure which starts off as a circumferential failure but then propagates down the pipe in a spiral fashion.

Figure 2.9 Circumferential Break in a Cast Iron Pipe (WSAA 2003)

Longitudinal Breaks

Longitudinal breaks are caused by transverse or hoop stresses and occur along the pipe wall. Figure 2.10 shows a longitudinal break on a cast iron pipe. Figure 2.7 illustrates the mechanisms leading to longitudinal breaks.

Rajani and Kleiner (1999) discuss causes of longitudinal breaks including hoop stresses due to internal pressure in the pipe or ring stress due to soil cover load, imposed live traffic loads or penetrating frost loads. Rajani and Makar (2000) and Makar et al (2001) outline similar failure mechanisms for longitudinal pipe failures.

Figure 2.10 Longitudinal Split in a Cast Iron Pipe

Blowout/Pin Holes

Hole failures in water mains typically consist of a small section being blown out of the wall of a pipe as shown in Figure 2.11 or a small pin hole leak occurring due to deterioration of the pipe wall shown in Figure 2.12.

Makar (2000) and Makar et al (2001) show that blowout holes may be caused by corrosion only or a combination of corrosion and internal pressures. Hu and Hubble (2007) distinguish between failures due to corrosion and internal pressure and failures due to corrosion describing the former as blowouts and the latter as pinholes.

Figure 2.11 Blowout in a Ductile Iron Pipe

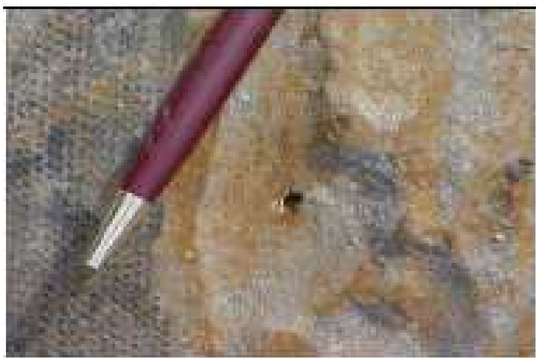

Figure 2.12 Pinhole Leak in a Ductile Iron Pipe (WSAA 2003)

Joint Failures

Joint failures include leaking joints, split or sheared collars and disconnected joints. Figure 2.13 illustrates a pipe failure caused by a perished lead joint.

Makar et al (2001) show that joint failures can be attributed to different thermal coefficients of expansion for jointing compounds or the pushing of a pipe spigot into the bell of the neighbouring pipe by compressive forces thus producing split bells.

Figure 2.13 Joint Failure Caused by Perished Lead Joint

2.3.5. Summary

As the importance of understanding and preventing water main failures comes to the fore, the number of studies on water main failures has been increasing. A review of some of these studies has highlighted the importance of maintaining complete and accurate water main failure records. It is vital to record as much data as possible at the time of the failure. In the past the value of this data wasn't fully recognised and this is reflected in the limited failure data available. As water main failure data recording systems improve so too will the understanding of the mechanisms that lead to water main failures.

As will be seen in the next section, failure modes and the mechanisms that cause these failures play an important role in the development of water main failure prediction models.

2.4. *Water Main Failure Prediction Models*

Many sources recognise the benefits of using modelling techniques to predict water main failures. Organisations that have made significant progress in this area include the NCRC in Canada and CSIRO in Australia. The purpose of this part of the literature review is to investigate some of the techniques used in existing water main failure prediction models.

2.4.1. What is a Water Main Failure Prediction Model?

The ultimate aim of a water main failure prediction model is to predict the time until failure for individual water mains taking into account the actual physical conditions of a water main and its environment.

The cost and complexities of obtaining the necessary data for developing a model to predict individual water main failures has meant this is not a realistic option for most authorities. To overcome this, a number of different failure prediction models using available data have been developed to predict the average rate of water main failures for pipe networks or pipe cohorts.

A comprehensive review of existing water main failure prediction models was carried out by Rajani and Kleiner (1999) and Kleiner and Rajani (2000). These reviews identified two types of failure prediction models – physically based and statistically based models.

2.4.2. Physically Based Models

Physically based failure prediction models attempt to use physical parameters to quantify the mechanisms that lead to pipe failure. The advantage of physically based models is the output of the model reflects the actual condition of the pipe and local environmental influences. The harsher the conditions acting on the pipe are, the shorter it's remaining useful life. A negative to physically based models is that the methods used are complex and require data that is difficult, if not impossible, for most authorities to obtain.

Rajani and Kleiner (1999) describe physical mechanisms that influence the structural performance and likelihood of failure of buried pipes including pipe structural properties, internal loads, external loads and material deterioration. Some models attempt only to address one or a few of these mechanisms, while others attempt to take a more comprehensive approach. Rajani and Kleiner's study reviews research conducted on three physical mechanisms frost loads, pipe-soil interaction and corrosion for inclusion in failure prediction models.

Frost Loads

A physical mechanism that attempts to explain the high frequency of water main failures in winter are frost loads. Rajani and Zhan (cited in Rajani and Kleiner 1999) presented methods to estimate frost loads acting on buried pipes in trenches. Frost loads are calculated using time, frost depth, frost heave, trench geometry and the soil characteristics of the backfill and trench sidewalls.

According to Rajani and Kleiner, calculated frost loads appear to agree with field measurements although further validation is required. Methods used are complex and input parameters may be difficult to obtain. Despite this, the work by Rajani and Zhan helps to explain the effects of frost loads on buried pipes.

Pipe-Soil Interaction

Another physical mechanism that attempts to explain the structural performance of buried pipes is the pipe-soil interaction. Rajani et al (cited by Rajani and Kleiner 1999) developed a pipe–soil interaction analysis model to determine the in plane and longitudinal stresses acting on a pipe taking into account pipe and soil characteristics, temperatures, internal pressures and external loads. The model appears to be successful in explaining the high frequency of failures during colder months and in small diameter mains.

Rajani and Kleiner noted some limitations with the model including failure to take into account soil shrinkage during dry months or existing pipe degradation. Data required for the models is readily available except for soil reaction moduli and ground temperatures.

Corrosion

A major physical mechanism that leads to water mains failures is corrosion. Various studies have been conducted looking at explaining how corrosion leads to failure including those by Kiefner and Vieth, Rajani et al and Kumar et al (all cited by Rajani and Kleiner 1999).

Kiefner and Vieth developed an analytical failure model for steel pipes in the gas industry to determine the pressure at which a corrosion pit would fail. Measurements required for the model are expensive to obtain and it is not known whether the model is appropriate for cast or ductile iron pipes.

Rajani et al conducted an experimental study on cast iron pipe to determine the nominal tensile stress at which fracture took place based on material and corrosion pit dimensions. Further validation is required on this study.

Kumar et al proposed modifying for the water industry a corrosion status index originally developed for the gas industry. More research needs to be conducted into the validity of these methods.

Rajani and Kleiner further classified physically based models into deterministic and probabilistic models.

Deterministic Models

Physical deterministic models attempt to relate corrosion pit depth and age to remaining wall thickness. Various models have been proposed by Doleac, Doleac et al, Randall-Smith et al and Rajani and Makar (all cited by Rajani and Kleiner 1999).

Doleac et al developed a model based on the power function proposed by Rossum (cited by Rajani and Kleiner 1999) to relate corrosion pit depth with pipe age to predict the remaining wall thickness of pit cast mains. The average wall thickness was then used to calculate pipe hoop stress. Pipe failure was defined as the point where a pressure surge of 50% of the working pressure raised the hoop stress to the material's elastic limit.

Randall et al proposed a linear model to estimate the remaining service life or residual life of water mains. This model was based on an assumption that corrosion pit depth has a constant growth rate. Rajani and Kleiner question the validity of this assumption.

Rajani and Makar described a methodology to estimate the remaining service life of grey cast iron mains. This method was based on studies previously mentioned including frost loads, pipe soil interaction and corrosion and employed methods developed by Doleac et al. The method proposed by Rajani and Makar is limited by uncertainties in estimating corrosion rates and needs to be validated against field data.

Probabilistic Models

Physical deterministic models attempt to predict the probability of failure based on parameters such as residual strength. Rajani and Kleiner cite a number of physical probabilistic models such as those by Ahammed and Melchers (1995) and Hong (1997. Many of these have been developed for the oil and gas industry and do not strictly apply to water mains. Another limitation of probabilistic models is the difficulty in predicting the effects of corrosion.

In summary, Rajani and Kleiner conclude that physically based modelling is more robust than other methods and the ultimate goal in failure prediction as it eliminates the need for statistics in identifying breakage patterns. However, physically based modelling has a number of limitations including complex methods and data that is impossible or expensive to obtain.

2.4.3. Statistical Models

The study by Kleiner and Rajani (2000) defines statistical models as those that use available historical data on past failures to identify pipe breakage patterns. These patterns are then assumed to continue into the future in order to predict the future breakage rate of a water main or its probability of breakage. The life of a buried pipe is described by the bathtub curve illustrated in Figure 2.14. The bathtub curve contains three distinct phases including burn in, in usage and wear out. Most models tend to deal with the wear out phase only because failure records are not usually available for the whole life cycle of a pipe.

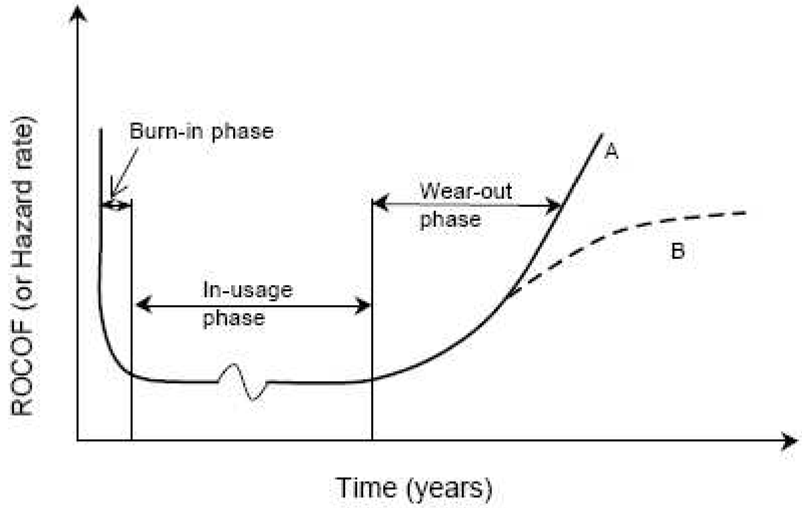

Figure 2.14 - Life of a Buried Pipe

Kleiner and Rajani consider two classes of statistical models – deterministic and probabilistic.

Deterministic Models

Kleiner and Rajani looked at two types of deterministic models including time-exponential and time linear models.

Time exponential models attempt to relate a pipe's breakage to the exponent of its age. Shamir and Howard (1979) proposed a simple two parameter model. Walski and Pelliccia (1982) sought to enhance this model by proposing extra parameter to take into account previous breakages and different breakage rates in different size mains. Clark et al (1982) proposed further improvements by transforming it into a two phase model comprising of a linear equation describing time until first break and an exponential model to describe subsequent failures. Time linear models assume a linear relationship between pipe breaks and age. Models have been developed by Kettler and Goulter (1985), McMullen (1982) and Jacobs and Karney (1994). Kleiner and Rajani observed that although simple to apply, deterministic models are best applied to homogenous groups of water mains.

Probabilistic Models

Kleiner and Rajani looked at two groups of probabilistic models - Multi-variate and Single-variate Group-Processing Models. Limitations of these models are that they require significant technical expertise and data to apply and hence will not be discussed in detail here.

Multi-variate probabilistic models include proportional hazard, accelerated lifetime and time dependent poisson models. These models can consider many covariates influencing breakage patterns which means the need to group water mains into homogenous groups is reduced.

Probabilistic single-variate models include cohort survival, bayesian diagnostic, break history as a semi-Markov process and break clustering models. These models use probabilistic processes on grouped data to derive probabilities of pipe life expectancy, probability of breakages and analysis of break clustering phenomenon.

Kleiner and Rajani conclude that despite the limitations of statistical methods of failure prediction it remains an economically viable approach for analysing failures in smaller diameter mains.

2.4.4. Alternative Models/ Improvements to Existing Models

Along with the models reviewed by Rajani and Kleiner (1999) and Kleiner and Rajani (2000) a number of other models have been suggested. Achim et al (2007) proposed the use of neural networks to predict water pipe asset life. Preliminary findings suggest that more accurate results can be achieved than those obtained from common statistical models. Studies are continuing. Dehgan et al (2008) proposed a non-parametric approach for the probabilistic failure prediction for deteriorating pipelines. This is a generic method based on interfailure times that can be used for infrastructure systems that deteriorate over time.

Other studies have concentrated on the improvement of existing models. Kleiner and Rajani (2000a) suggests modifying existing time exponential models to include time-dependent factors such as freezing indexes, rain deficit, pipe replacements and pipes retrofitted with cathodic protection. Kleiner and Rajani (2002) carried out further studies which also included climate forecasting. Results obtained were more accurate than previous modelling without the time-dependent factors. Davis et al (2003) and Sadiq et al (2004) propose techniques for improving the understanding of soil effects on water main failures using GIS mapping and fuzzy-based methods. Mavin (1996) suggested the need to filter data to remove records pertaining to failures imposed by external factors in order to remove bias and get a true indication on the deterioration of the system.

2.4.5. Summary

From this review of existing literature pertaining to water main failures it can be seen that the performance of buried pipes and the modes in which they fail are generally agreed upon. The mechanisms that cause failure are complex and more understanding is coming to light as data sets grow and studies continue to be carried out. To further this understanding it is important that authorities continue to collect water main failure data in a consistent format that can be compared with other authorities.

Many water main failure prediction models have been developed to predict the future performance of a water supply network. The two main types of models are physically based models and statistical models.

Physically based models are more robust than statistical models and the ultimate goal in failure prediction as it eliminates the need to use statistics to identify breakage patterns. However, physically based modelling has a number of limitations including complex methods and data that is difficult or expensive to obtain. As data collection systems are improved and non destructive water main evaluation techniques are developed physically based models will become more readily used.

Despite the limitations of statistical methods of failure prediction it remains an economically viable approach for analysing failures in smaller diameter mains. Further enhancements to existing statistical models to include static and dynamic factors other than the standard pipe age can only improve the effectiveness of these models.

The choice of method used for a water main failure prediction model is based on data availability and the complexity of the method. The biggest limitation is data availability both from historical records and in obtaining data needed to apply given models.

2.5. Chapter Summary

This chapter provides a comprehensive review and analysis of published literature and studies relating to water main failure analysis and failure prediction modelling. The three areas covered in the review include the structural design of buried pipes, causes and types of water main failures and methods and parameters used in existing water main failure prediction models. Research shows that, although the structural design of buried pipes is well accepted, the causes of failure are complex and not fully understood. A number of different failure prediction models of varying complexity have been proposed to describe water main failures. Choice of model is limited by the type and quality of water main failure data available.

CHAPTER 3

METHODOLOGY

3. Methodology

3.1. Introduction

This chapter describes the methods that were used in conducting the study. More specifically the literature review, the analysis of Actew water main failure data, collation of raw data and the regression analysis used in developing the customised water main prediction models.

3.2. Literature Review

The literature review has been previously discussed in Chapter 2. The review was carried out to gain an understanding of the body of knowledge that exists relating to water main failures and how this can help in developing water main failure prediction models. The review of buried pipe design and the causes of water main failures formed the background for the analysis of ACT water main failure records conducted in Chapter 4. The results of this failure analysis along with a consideration of failure prediction model types and existing models assisted in the selection of the model type developed in Chapter 5.

3.3. ACT Water Main Failure Data Analysis

The purpose of carrying out an analysis of water main failure data in the ACT was to 1) identify limitations in the data that could affect the type of model developed, 2) determine whether the factors identified in the literature review are also influential in failures in the ACT and 3) identify factors that could be incorporated into a customised water main failure prediction model.

The data analysis discussed in Chapter 4 was carried out using the following methods.

- Compile historical failure records together and assess the quality and limitations of available data.
- Conduct a general analysis of water main failure data using the factors identified in the literature review.
- Plot water main failures on a map of the ACT and identify and analyse any failure trends or patterns.
- Plot water main failures on a graph at time intervals of one month and one year and identify any failure trends or patterns.

3.4. Collation of Data

All data used in the model has been obtained from existing Actew water main failure records or online climate data records from the Bureau of Meteorology. Raw data used in the development of the model is included in Appendix B.

- Twelve Monthly Water Main Failure Totals
- Time (month or year)
- Twelve Monthly Rainfall Totals
- Twelve Monthly Totals of Days where the minimum ground temperature was equal or lower than -1° C

Twelve monthly water main failure totals have been compiled from existing Actew water main failure records for the period between July 1978 and June 2008. Note some moderation of these totals has taken place to account for periods where failure records are missing or incomplete.

Rainfall and ground temperature data are available for the Canberra Airport weather station from the Bureau of Meteorology website. The airport is located approximately 7 kilometres due east of the city centre. Although the weather conditions vary slightly across the city, the airport location has been selected due to its approximate central location.

Rainfall data consists of monthly rainfall totals and ground temperature data the number of days in a month where the minimum ground temperature was equal or lower than -1° C. Twelve monthly totals were used in the model.

3.5. Model Development

The two customised water main failure prediction models discussed in Chapter 5 were developed using multiple regression techniques. All multiple regression analyses were carried out using data analysis methods in the software package Microsoft Excel.

3.5.1. Regression Analysis

The objective of multiple regression analysis is to predict the change in a dependent variable in response to the changes in a set of given independent variables. The dependent variable is the parameter to be predicted by the model and the independent (or explanatory) variables are the model input parameters.

The basic procedure used in developing a multiple regression model is to keep adding explanatory variables to the model based on their correlation with the dependent variable while analysis shows that their inclusion significantly improves the accuracy of the model. Correlation is determined by performing a correlation analysis, while the value of adding variables to the model is determined by performing a regression analysis and partial F-test. An explanation of some of these processes is provided.

Correlation Analysis

Correlation analysis is used to measure the degree of association between numerical variables. A correlation of 1 denotes a perfect positive correlation, 0 no correlation and -1 a perfect negative correlation. Correlation analysis is performed using the Data Analysis tool in Microsoft Excel. An example of a correlation matrix produced in Excel is shown in Table 3.1.

Table 3.1 Example of a Correlation Matrix

	No Of Failures	*Time*	*Rain*	*Temp*
No Of Failures	1			
Time	0.862047711	1		
Rain	-0.340968677	-0.10655	1	
Temp	0.19501653	0.058149	-0.58751	1

The formula used to calculate the correlation coefficient is outlined in Figure 3.1 below.

Figure 3.1 Correlation Coefficient Formula

$$r = \frac{\sum_{i=1}^{n}\left(X_i - \overline{X}\right)\left(Y_i - \overline{Y}\right)}{\sqrt{\sum_{i=1}^{n}\left(X_i - \overline{X}\right)^2}\sqrt{\sum_{i=1}^{n}\left(Y_i - \overline{Y}\right)^2}}$$

where	r	=	Correlation Coefficient
	X_i	=	X Value at point i
	$\overline{X}$	=	Mean of X
	Y_i	=	Y value at point i
	$\overline{Y}$	=	Mean of Y

Regression Analysis

A regression analysis is performed using the Data Analysis tool in Microsoft Excel. An example of the output from Excel is shown in Figure 3.2. The three main parts of this output are the regression statistics, analysis of variance (ANOVA) and residual outputs.

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.862047711
R Square	0.743126256
Adjusted R Square	0.742408731
Standard Error	61.10799069
Observations	360

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	3867425.213	3867425.213	1035.68078	1.068E-107
Residual	358	1336838.776	3734.186526		
Total	359	5204263.989			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	226.369329	6.427951562	35.21640243	2.37E-118	213.7280395	239.0106186	213.7280395	239.0106186
X Variable 1	0.997354403	0.030991069	32.18199465	1.068E-107	0.936406982	1.058301825	0.936406982	1.058301825

RESIDUAL OUTPUT

Observation	*Predicted Y*	*Residuals*	*Standard Residuals*
1	226.369329	36.63067098	0.600278213
2	227.3666834	37.63331657	0.616708879
3	228.3640378	34.63596217	0.567590299
4	229.3613922	22.63860777	0.370985916
5	230.3587466	5.641253362	0.092444976
6	231.356101	-3.356101042	-0.054997473
7	232.3534554	3.646544555	0.059757061
8	233.3508098	10.64919015	0.174511595
9	234.3481643	7.651835748	0.125393015
10	235.3455187	-2.345518655	-0.038436745
11	236.3428731	-8.342873059	-0.136717259
12	237.3402275	-7.340227462	-0.120286593

Figure 3.2 Sample Output from Regression Analysis in Excel

The coefficient of determination is equal to the regression sum of squares divided by the total sum of squares and measures the proportion of variation explained by the independent variable in the regression model. The closer to 1 the coefficient is, the better the independent variables are able to explain variation in the dependent variable.

The coefficient of multiple determination is calculated using the formula shown in Figure 3.3 where SSR is regression sum of squares and SST is the total sum of squares. To account for the number of explanatory variables in the model and the sample size the coefficient is adjusted using the formula in Figure 3.4.

Figure 3.3 Coefficient of Multiple Determination Formula

$$r_{Y.12}^2 = \frac{SSR}{SST}$$

Figure 3.4 Adjusted Coefficient of Multiple Determination Formula

$$r_{adj}^2 = 1 - \left[\left(1 - r_{Y.12...P}^2\right) \frac{n-1}{n-P-1} \right]$$

The ANOVA analysis is used to test the significance of the relationship between the dependent variable and the explanatory variables. This is done using the F test to analyse the ratio of the regression mean square to the error mean square. Output of the ANOVA analysis and the relevant calculations are shown in Table 3.2.

In the F test the calculated F statistic is compared to a predetermined critical F value based on a selected level of significance and the number of variables in the model. For the results to be considered significant the F statistic must be greater than the critical value.

Table 3.2 ANOVA Table

Source	df	Sums of Squares	Mean Square (Variance)	F
Regression	P	$SSR = b_0 \sum_{i=1}^{n} Y_i + b_1 \sum_{i=1}^{n} X_{1i} Y_i + b_2 \sum_{i=1}^{n} X_{2i} Y_i - n\bar{Y}^2$	$MSR = \frac{SSR}{P}$	$F = \frac{MSR}{MSE}$
Error	n -P-1	$SSE = \sum_{i=1}^{n} Y^2_i + b_0 \sum_{i=1}^{n} Y_i + b_1 \sum_{i=1}^{n} X_{1i} Y_i - b_2 \sum_{i=1}^{n} X_{2i} Y_i$	$MSE = \frac{SSE}{n - P - 1}$	
Total	n-1	$SST = \sum_{i=1}^{n} Y^2_i - n\bar{Y}^2$		

where df = degrees of freedom
P = number of explanatory variables in the model
n = sample size
SSR = regression sum of squares
SSE = error sum of squares
SST = total sum of squares
MSR = regression mean square
MSE = error mean square

Partial F-Test Criterion

The partial F-test criterion is used to determine the significance of adding variables to the model. This involves determining the contribution to the regression sum of squares made by each explanatory variable after all the other explanatory variables have been added to the model.

The process used to carry out the partial F test is similar to that for the F test except SSR is calculated using the formula expressed in Figure 3.5 and hence the partial statistic is calculated using the formula in Figure 3.6. If the partial F value is less than the critical F value then inclusion of the explanatory variable in the model will not significantly improve model accuracy and the variable should be omitted from the model.

Figure 3.5 Adjusted Coefficient of Multiple Determination Formula

SSR (X_k | All variables except k) = SSR (All variables including k)-SSR (All variables except k)

Figure 3.6 Partial F Test Criterion Formula

$$F = \frac{SSR(X_k | all\_variables\_except\_k)}{MSE}$$

3.5.2. Testing of the Significance of the Model

Once the models were completed testing was carried out to determine the significance of the model by considering the adjusted coefficient of determination, residuals analysis and partial regression plot analysis.

As mentioned previously, the closer the coefficient of determination is to 1 the more accurately the explanatory variables in the model are able to account for the variation in the dependent variable. A low coefficient of determination suggests scope for improvement in the model.

Residual analysis is conducted to identify violations of the four assumptions of regression analysis which include normality, homoscedasticity (or constancy of error), independence of residuals and linearity. Some of the problems that may be identified include an uneven spread in the distribution of residuals over the range of the dependent variable indicating lack of homoscedasticity and trending in the residuals over time indicating autocorrelation.

Partial regression plots illustrate the relationship between the dependent variable and individual explanatory variables. For the regression model to be valid these plots should confirm a linear relationship for all independent variables.

3.6. Chapter Summary

This chapter provides details of the methodology used in conducting the study. It highlights the relevance of conducting the literature review and the water main failure analysis in order to facilitate the development of a customised prediction model and discusses the specific methods of each of these tasks including providing a background to regression analysis.

CHAPTER 4

ACTEW WATER MAIN FAILURE DATA ANALYSIS

4. Actew Water Main Failure Data Analysis

As previously discussed in Chapter 3, the purpose of reviewing historical failure records is to identify data limitations that will influence the type of failure model to be developed, identify factors that can be used to explain the type and frequency of failures in the ACT and to identify data improvements that will enhance future failure analysis capabilities.

4.1. ACT Water Supply Network

The ACT water supply network (shown in Figure 4.1) is made up of more than 3000 kilometres of water mains and continues to increase at a gradual rate. Although the first water mains were laid in the ACT approaching 100 years ago, the majority of the network is less than 50 years old. Figure 4.2 shows the growth of the ACT water distribution system over time. Notable features include the rapid growth of the system during the 1960's and 1970's, the superseding of cast iron by ductile iron in 1982 and the acceptance of PVC as an alternative to ductile iron in 1994.

Tables 4.1 and Table 4.2, taken from the current Actew Corporation Asset Management Plan (2008), show the current pipe size and pipe material distributions for the ACT. From the pipe size distribution it can be seen the most common pipe sizes in the ACT are 100mm and 150mm making up approximately 70% of the existing network. The pipe material distribution shows that cast iron makes up the biggest proportion of the network, followed by ductile iron and then mild steel, asbestos cement and PVC. Older pipe materials in the network include cast iron, mild steel and asbestos cement, while relatively newer pipe materials include ductile iron and PVC.

Table 4.1 Pipe Size Distribution

Pipe Sizes	% of Existing System
100	45.5
150	25.0
225	9.5
300	5.0
>300	14.0

Table 4.2 Pipe Material Distribution

Pipe Material	Period of Use	% of Existing System
Cast Iron	1915 to 1982	63.5
Ductile Iron	1983 to present	20.0
Mild Steel	1954 to present	9.0
Asbestos Cement	1939 to 1961	7.0
PVC	1994 to present	0.5

4.2. Actew Water Main Failure Records

4.2.1. Overview

Actew has water main failure records dating back to the 1970's. These records span a number of data collection systems of varying quality and format including hard copy and electronic records. The importance of keeping and maintaining comprehensive failure records was not recognised until relatively recently and therefore many historical records are incomplete or only cover part of the network.

To assist in failure analysis, some ongoing work is being conducted to clean up and compile historical records into a more useful format. This includes adding missing details where available, filtering out errors and moderating failure rates to account for missing records. Although this has improved the quality of data available more work is still required to increase the usefulness of this data.

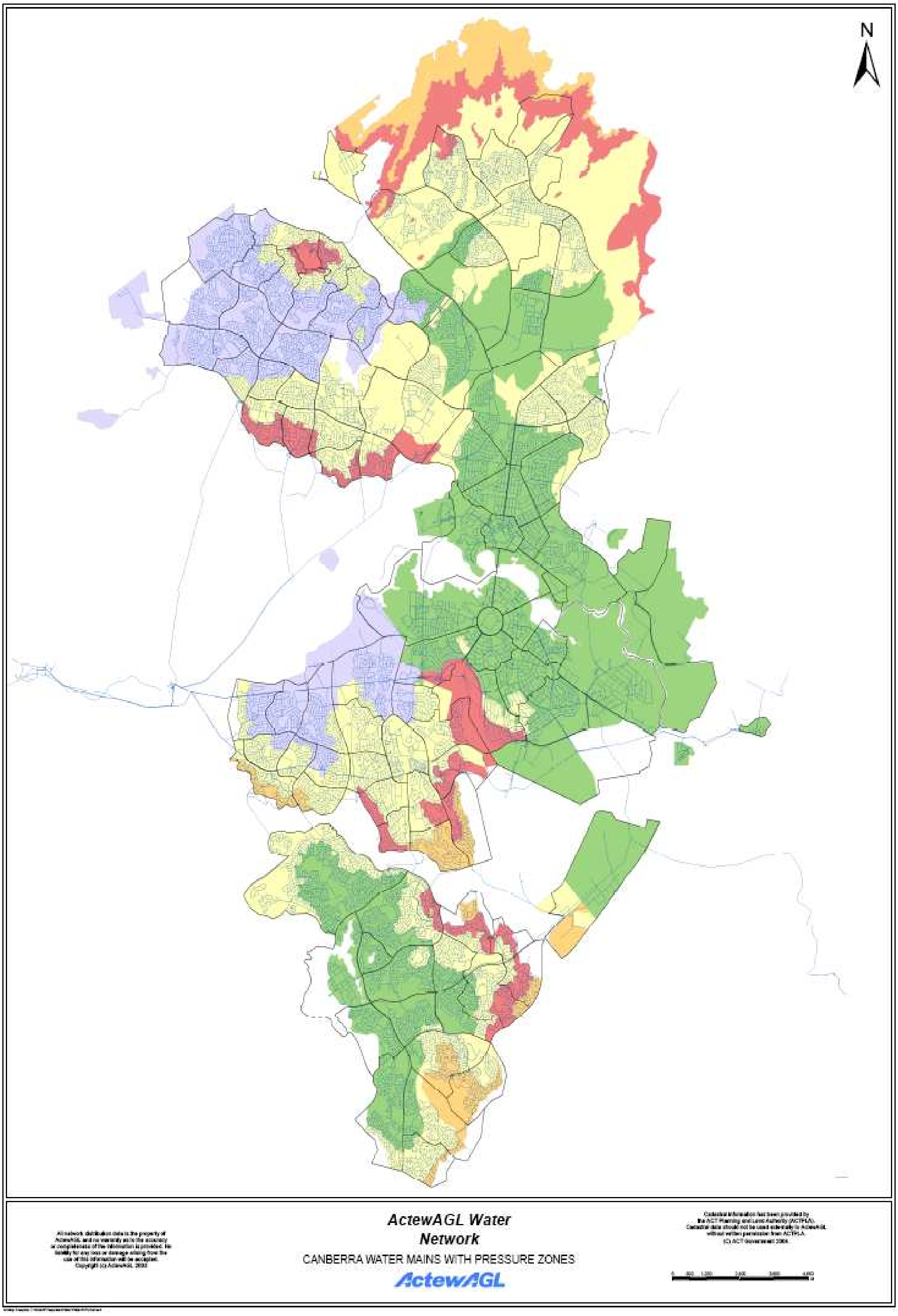

Figure 4.1 – ACT Water Supply Network Layout

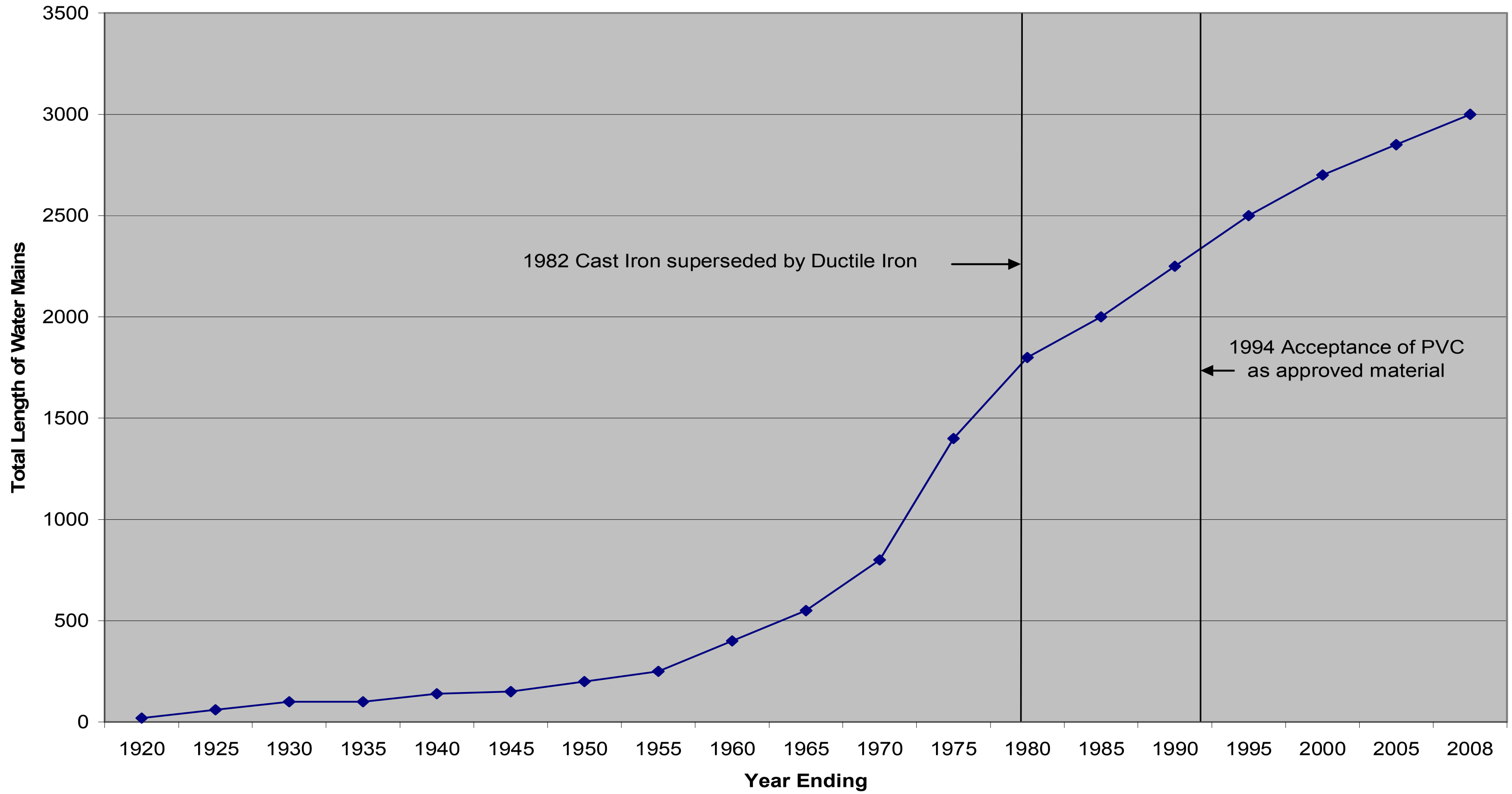

Figure 4.2 - Growth of ACT Water Supply Network over Time

Confirmed and reliable data covering the entire network is only currently available from July 1997. Typical job details recorded include location, pipe size, pipe material, ground cover over main, failure mode, repair type and number of customers affected.

4.2.2. Adequacy of Existing Failure Records

Record keeping practices have gradually been improving as the importance of failure analysis has been recognised. Despite this the current data set doesn't lend itself to easy failure analysis. The main issues relate to the completeness of the data, ease of data manipulation, compatibility with the mapping system and the extent of details being recorded for each failure.

The ability to carry out failure analysis is limited by the completeness of available data. Although total number of failures can be determined with some certainty back to the 1970's, other details can not be traced back more than 10 years. This makes it difficult to determine influential factors in the failure rates over this period. Further compilation of data is required to fill in missing details where possible. The more comprehensive the data available, the better it will be for failure analysis and future model developments.

The format of existing failure records makes it difficult to manipulate data in order to carry out failure analysis. Historical records are stored in a number of different spreadsheets and within worksheets in those spreadsheets. The format between spreadsheets also varies slightly. This makes it difficult to compare data across different time periods. Failure analysis can be improved by compiling all spreadsheets and worksheets into one central database. This will make it easier to interrogate data from the failure records.

Failure analysis is also limited by the difficulty in linking failure records to the mapping system. The mapping system provides access to pipe asset details and also assists in the spatial analysis of failures but must be linked through a unique asset identifier. Most historical records do not include this identifier and must be linked indirectly. Failure analysis will be greatly improved by having a direct link between failure records and the mapping system. Record keeping practices have been changed recently to include asset facility codes. Compilation of historical records should also include the addition of a facility code where possible.

The range of failure data currently being recorded has improved but is still fairly basic. Only limited physical data is being recorded which limits the amount of physical analysis that can be carried out. Failure analysis can be improved by broadening the scope of physical data being recorded.

4.2.3. Water Works

Water main failure records are currently collected through Water Works which is the works management system used by ActewAGL Water Division's Field Services Branch. Since its inception in 2005 Water Works has improved the data collection and analysis capabilities for all jobs including water main failures.

Routine information collected in Water Works includes location, pipe size, pipe material, ground cover over main, failure mode, repair type and number of customers affected. Recently a facility code, or unique asset identifier, was also included for the failed pipe. This provides a direct link between the failed pipe and the mapping system which allows asset details to be found later on if they are not collected at the time of the failure.

Figure 4.3 illustrates a typical water main failure record from Water Works. Noticeable features displayed in the record include the coded check lists outlining the specific details of the job and the facility code which is the unique identifier for the failed pipe.

Figure 4.4 illustrates the search capabilities of Water Works. Records can be filtered by date or any of the other coded checklists including pipe size, pipe material, failure type and repair type. This allows more thorough failure analysis to be carried out on historical data recorded in Water Works.

Although the type of data recorded in Water Works is still very basic, the scope exists to expand the range of data collected to include physical parameters also.

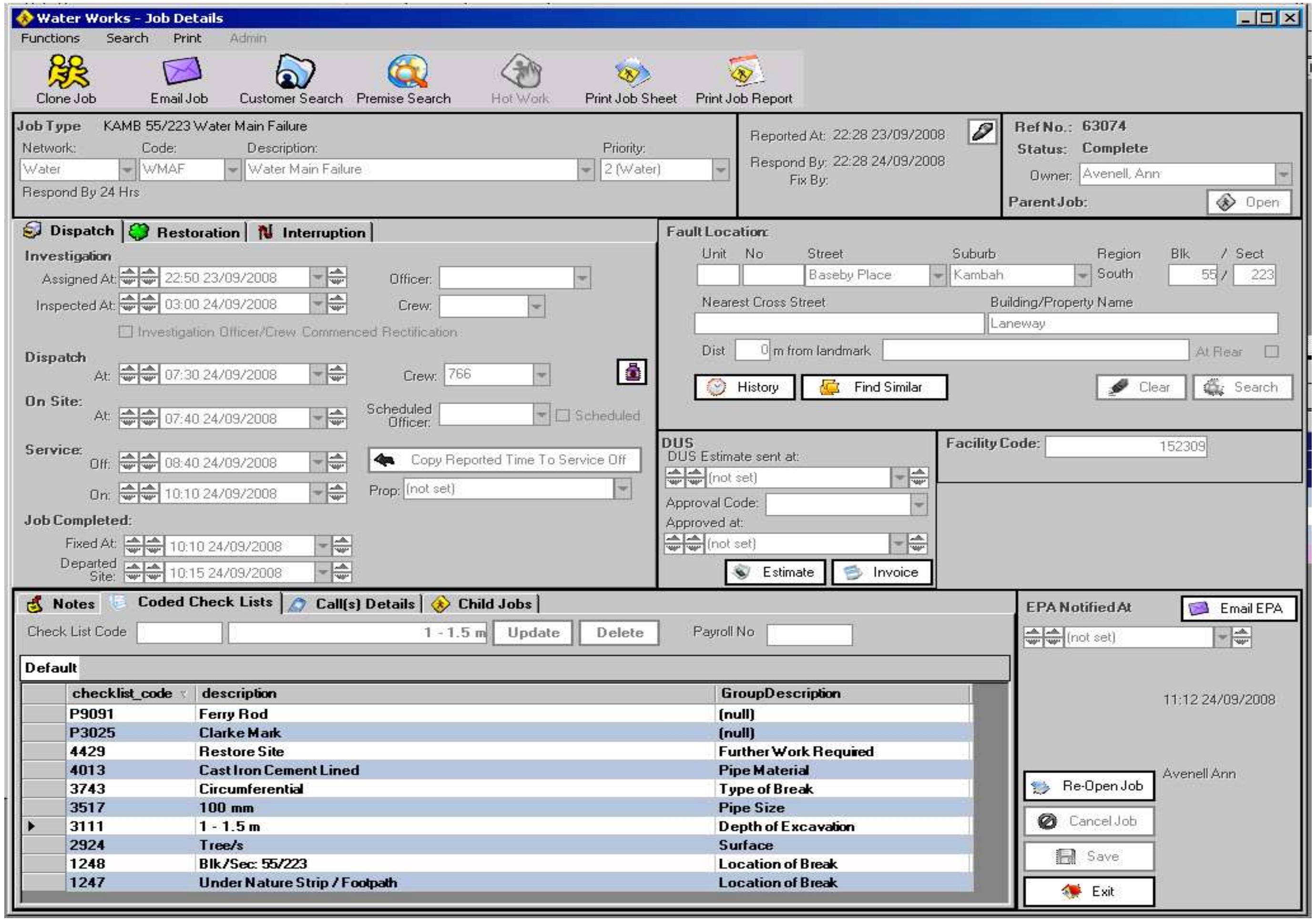

Figure 4.3 – Sample Water Main Failure Record from Water Works

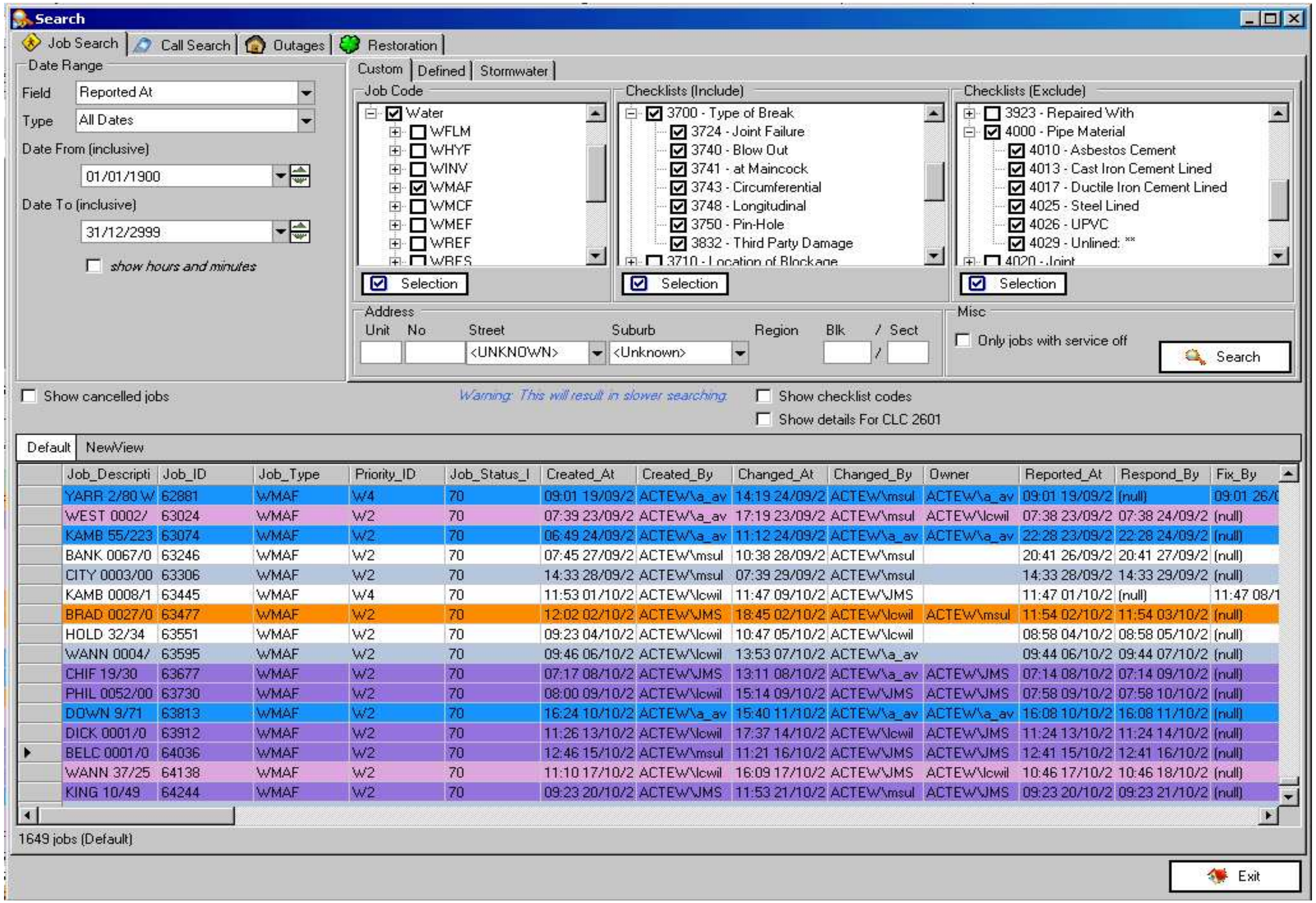

Figure 4.4 -Water Works Search Function

4.3. Previous Data Analysis

Despite limitations in the existing dataset, some statistical analysis has been carried on water main failures in the ACT. For example, a draft report by McRae (2007) was carried out to investigate failures and trends in the ACT water supply network. The purpose of this investigation was to supply background information for Actew's asset management plan and regulatory licensing conditions.

A summary of the findings show that overall water main failure rates in the ACT are relatively low. Some parts of the network experience a higher failure rate with grouping or clustering of failures. Most failures are associated with small diameter cast iron water mains installed in the 1960's and 1970's. Ductile iron pipe failures appear to be increasing.

4.4. Data Analysis

The literature review highlighted many factors that contribute to and have an influence on the likelihood of water main failure. The following discussion will look at some of these factors to see what role they play in water main failures in the ACT.

4.4.1. General Analysis

<u>Pipe Age</u>

As previously discussed, it can be expected that failure rates will increase over time as pipes deteriorate and reach the end of their useful lives. Analysis shows that this also appears to be the case in the ACT.

Limitations in the existing dataset prevent installation year from being easily obtained from the asset data contained in the mapping system.

Therefore, suburb age, material type and the overall failure trend (all discussed in subsequent sections) have been used as an indicator of the effect of pipe age on failure rates.

Spatial analysis shows that the majority of water main failures occur in suburbs that were developed prior to 1980 and that failures in suburbs developed after this year are rare. This suggests pipe age has a significant effect on the likelihood of pipe failure.

Pipe material reflects the relative age of a pipe. Up until 1982 cast iron was the preferred pipe material. After 1982 cast iron was no longer allowed and ductile iron became the approved material. In 1994 PVC was also allowed as an approved material. Analysis has shown that the majority of failures occur in the older cast iron pipes in the network.

Temporal analysis of water main failures shows that the overall failure rate has gradually been increasing over time. This reflects the relative age of the network. Failure rates are increasing as a greater number of pipes reach the end of their useful lives.

Pipe Size

Pipe size has a direct influence on the likelihood of failure. Pipes with a smaller diameter are more prone to failure. As illustrated in Table 4.3, of the 4131 water main failures in the ACT between 2001 and 2008, 94% occurred in 100mm and 150mm water mains. This is not unexpected as approximately 71% of the ACT water main network is made up of 100 and 150mm pipes. Smaller diameter pipes also, having smaller wall thicknesses, are more susceptible to corrosion and excess loading.

Table 4.3 Pipe Failure by Size 2001 - 2008

Pipe Sizes	% of Failures
100	75
150	19
225	3
300	1
>300	2
Total number of failures	4131

Pipe Material

Pipe material appears to have some influence on the likelihood of failure. Table 4.4 shows that, of 2318 water main failures between 2004 and 2008, 90.5% were in cast iron pipe, 7% in ductile iron pipe and 2.5% were in PVC, asbestos cement and steel mains. This seems to suggest that iron pipes, particularly cast iron, are more susceptible to failure. Iron pipes can suffer from corrosion when laid in particularly aggressive conditions but on closer investigation this is likely to have more to do with the greater proportion of iron pipes in the network and the relative age of the pipes. Cast iron pipes make up more than 60% of the ACT water supply network ranging from about 26 to 93 years of age. Although relatively young in age, ductile iron pipe failures seem to be increasing. There does not appear to be a problem in other pipe material types.

Table 4.4 Pipe Failure by Material 2004 - 2008

Pipe Material	% of Failures
Cast Iron	90.5
Ductile Iron	7
PVC	1
Steel	1
Asbestos Cement	0.5
Total number of failures	2318

Failure Type

The type of failure mode helps to explain the mechanisms that have caused failure. ActewAGL uses seven categories to describe failure modes. Table 4.5 shows the percentage of failures by failure mode for the 1605 failures in the ACT between 2005 and 2008.

The high incidence of circumferential breaks suggests that frost loading, thermal effects and soil movement have a significant effect on water main failure rates. Temporal analysis of failure modes (discussed later) further backs this up. Particularly susceptible are small diameter cast iron water mains.

A noticeable number of longitudinal water main failures have occurred over the period from 2005 to 2008. This failure type is caused by external loading or pressure surges. A number of significant longitudinal failures have occurred in larger diameter mains caused by pressure surges.

Blowout and pinhole failures suggest the influence of corrosion and pressure. Corrosion has the effect of reducing pipe wall thicknesses to a point where a hole forms or the ability to resist pressure is reduced and a blowout occurs. Failures also occur at weak spots near where the maincock is tapped into the pipe requiring a new section of pipe to be replaced.

Joint failures are typically caused by problems with the lead caulking being displaced in older cast mains. This is usually a problem in larger diameter trunk mains.

Water main failures caused by third parties are rare but can cause major problems when they do occur. Typical causes include increased surface loading due to heavy vehicular traffic, undermining pipe support structures and failure to get proper asset locations.

Table 4.5 Pipe Failure Modes 2005 - 2008

Failure Mode	% of Failures
Circumferential	70
Blowout	10
Longitudinal	6
Joint Failure	4
Maincock	4
Pin Hole	4
Third Party Damage	2
Total number of failures	1605

Pressure

Pressure is also thought to have an influence on the likelihood of pipe failure. Some trunk water main failures in the ACT have been directly attributed to pressure surges in the system. Pressure reduction has been identified as a possible means of reducing the number of failures. The idea being that higher pressures make a weakened pipe more susceptible to failure and lowering the pressure reduces the likelihood of failure.

An investigation was carried out to determine the influence of pressure in failures in the suburb of Kaleen which experienced a relatively high failure rate. Results are shown in Figure 4.5. Of the 58 failures in Kaleen from 2005 to 2008 only 4 failures occurred in an area with an estimated static pressure less than 50 metres of head. This suggests that weakened pipes may be more susceptible to pressure and pressure reduction studies may be beneficial.

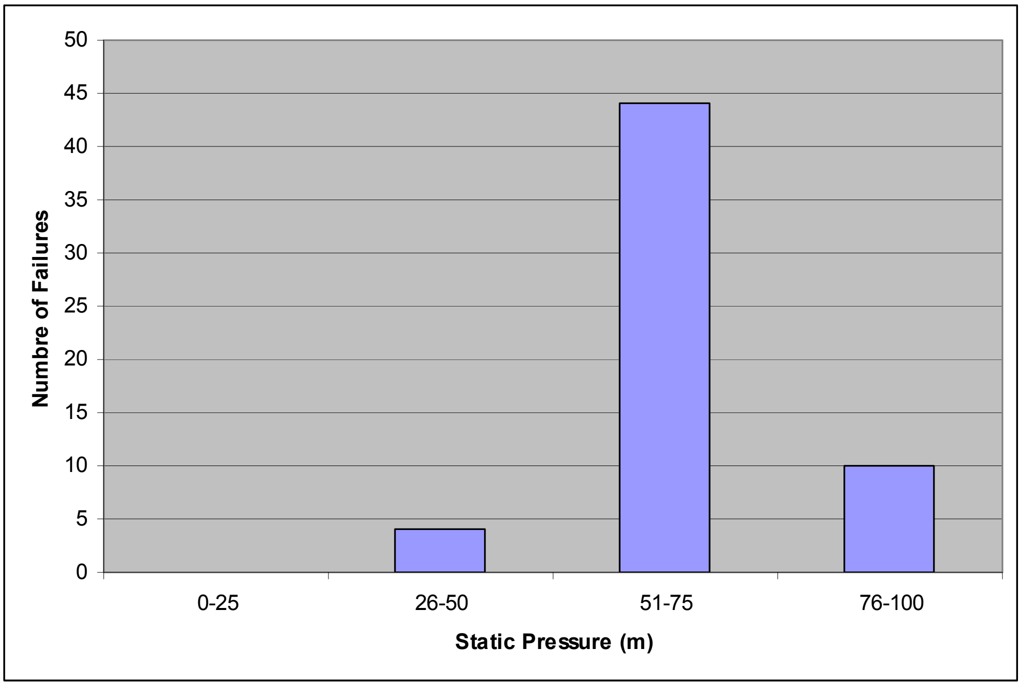

Figure 4.5 - Influence of Pressure on Kaleen Failures 2005 - 2008

4.4.2. Spatial Analysis

Spatial analysis involves plotting failures on a map and trying to determine if there are any geographical patterns in the failure distribution. Once a pattern is identified potential causes are then investigated.

Figure 4.6 shows water main failures for the period from 2005 – 2008 plotted on a map of the ACT. To illustrate the effect of pipe age on failure rate suburbs have also been colour coded according to the year they were first developed. Looking at the failure distribution it can be seen that a number of patterns are evident.

Firstly, there are three distinct failure densities that seem to reinforce what has been said earlier about the influence of pipe age and material type on failure rates. Most failures occur in cast iron pipes that were installed up until 1982 with a higher density of failures for pipes installed between 1961 and 1982. Failures in ductile iron or PVC pipes installed after 1982 are rare.

Interestingly, failures are more common in pipes installed in the 1960's and 1970's than pre 1960. This suggests factors other than age are also involved in water main failures. Some possible explanations for this include rapid development in the ACT during this time resulting in poor quality control, the change from sand cast to spun cast iron pipes which exhibit inferior corrosion resistance qualities or some other unique local influences.

Other grouping or clustering of failures within suburbs or other areas is also evident. This could be due to a number of localised influences or physical factors such as previous repairs, pressure, corrosion, embedment soil conditions and climatic conditions. As discussed previously, physical data can be difficult or costly to obtain and many of these influences constitute a study in themselves. For example, the effects of pressure reduction or soil type on failure rates. Financial and time constraints prevent studies being conducted at the moment but future studies may be beneficial.

Spatial analysis of water main failure distributions in the ACT has shown that failure patterns are evident. Some of these patterns can be explained by factors such as pipe age or pipe material. Other patterns suggest that various physical factors or localised conditions could also be relevant. Unfortunately, Actew only has limited physical data available and further studies would be needed to collect and analyse this data.

As far as developing a model is concerned, continuing investigation of physical failure influences would be beneficial in developing a physically based prediction model. This could be used to predict time to failure for individual water mains. However, to do this more physical data is required and current failure rates may not justify the collection of the data at this time.

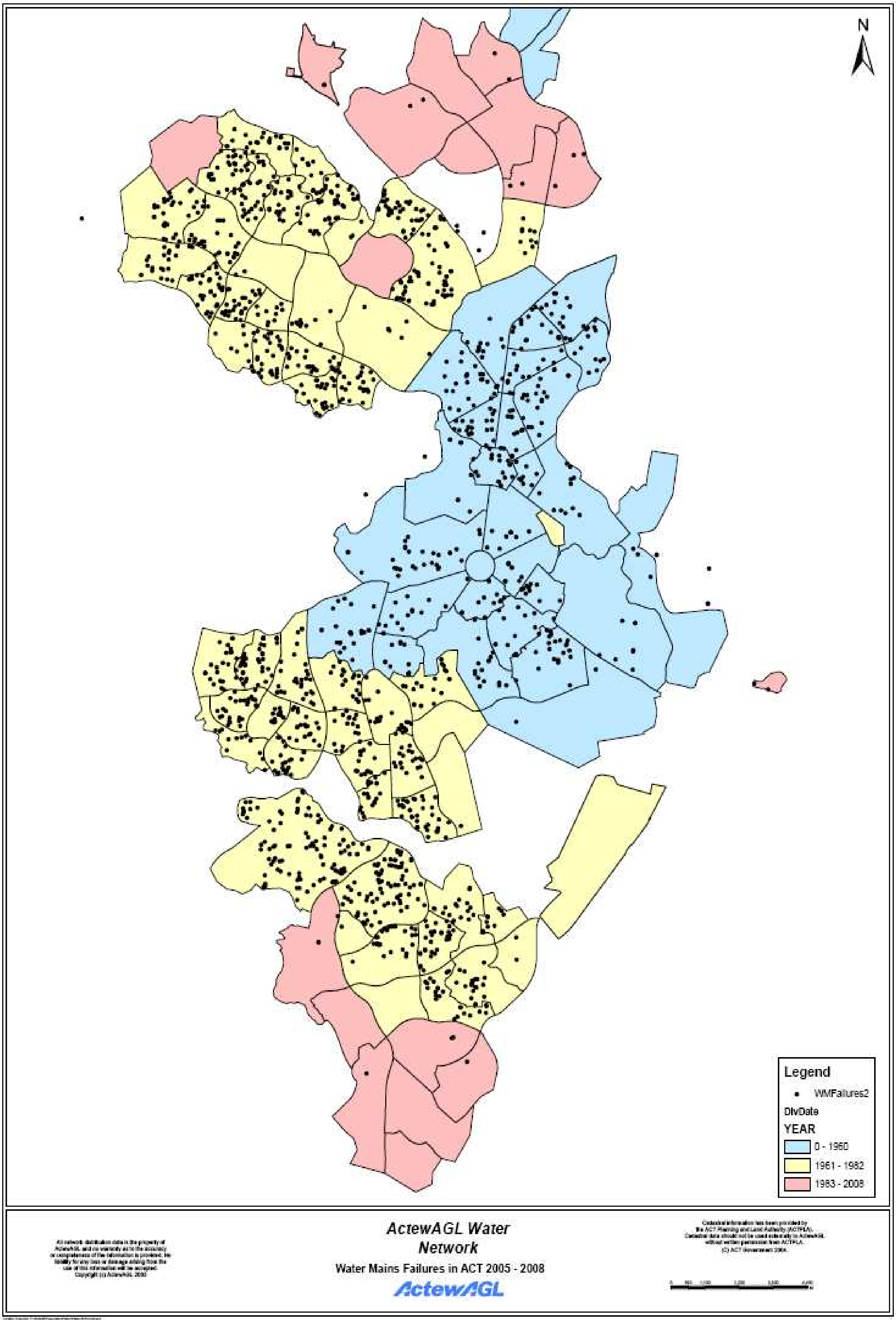

Figure 4.6 – Spatial Distribution of ACT Water Main Failures 2005 - 2008

4.4.3. Temporal Analysis

Temporal analysis involves plotting failures over time to see if any failure trends are evident. These trends may be short term, long term, cyclical or seasonal.

Figure 4.7 shows rolling twelve month failure totals for the ACT plotted for the period between 1978 and 2008. From the plot it can be seen that, despite fluctuations year to year, there is a general upward trend in the number of failures. The upward trend highlights the influence of time or age on the number of failures. Yearly fluctuations also suggest cyclical influences. Some of these cyclical influences may be due to climatic effects such as heavy rainfalls associated with La Nina or prolonged dry periods associated with drought.

Figure 4.8 shows monthly failure totals for the ACT plotted for the period between 1997 and 2008. Evident from the plot is a distinct seasonal influence. Failures are generally at a low around September/October, begin increasing again around April/May and peak at about 100 - 140 during the winter months. Some secondary peaks also occur during the summer months. For example, in January 2003 there were an unusually high number of 59 failures.

The peak failures in winter suggest cold temperatures are influential in failure rates. This is in harmony with the findings of the literature review which put forward frost loads, temperature induced tensile loadings and increased corrosion rates as possible causes for increased failure rates in winter.

The secondary peaks in summer seem to coincide with low rainfall periods. For example, peak failures in January 1998, 2003, and 2007 seem to coincide with dry periods of low rainfall. Figure 4.8 illustrates this well. Failure peaks seem to coincide with rainfall troughs and vice versa. This implies that perhaps soil moisture could be influential in failure rates. Drought results in soil drying and shrinking. This induces loading on a buried pipe making it more prone to failure.

Temporal analyses of water main failures in the ACT show strong temporal trends are evident relating to age/time, season – winter/summer and cyclical influences – drought, La Nina. Some of these factors could possibly be incorporated into a model to help explain the failure rates experienced in the ACT.

4.5. Findings

A summary of the findings of the Actew failure data analysis are outlined below.

- Actew has some water main failure records dating back to the 1970's.
- Some moderation of this data has taken place to account for missing or incomplete data.
- Most of the water main failure data collected is basic and lacks the physical data required to develop a physically based failure prediction model.
- Existing data is more suited to the development of a statistically based failure prediction model.
- The majority of failures occur in the ACT occur in small diameter (100mm and 150mm) cast iron water mains.
- Failure rates increase in the ACT during winter and also during low rainfall periods.

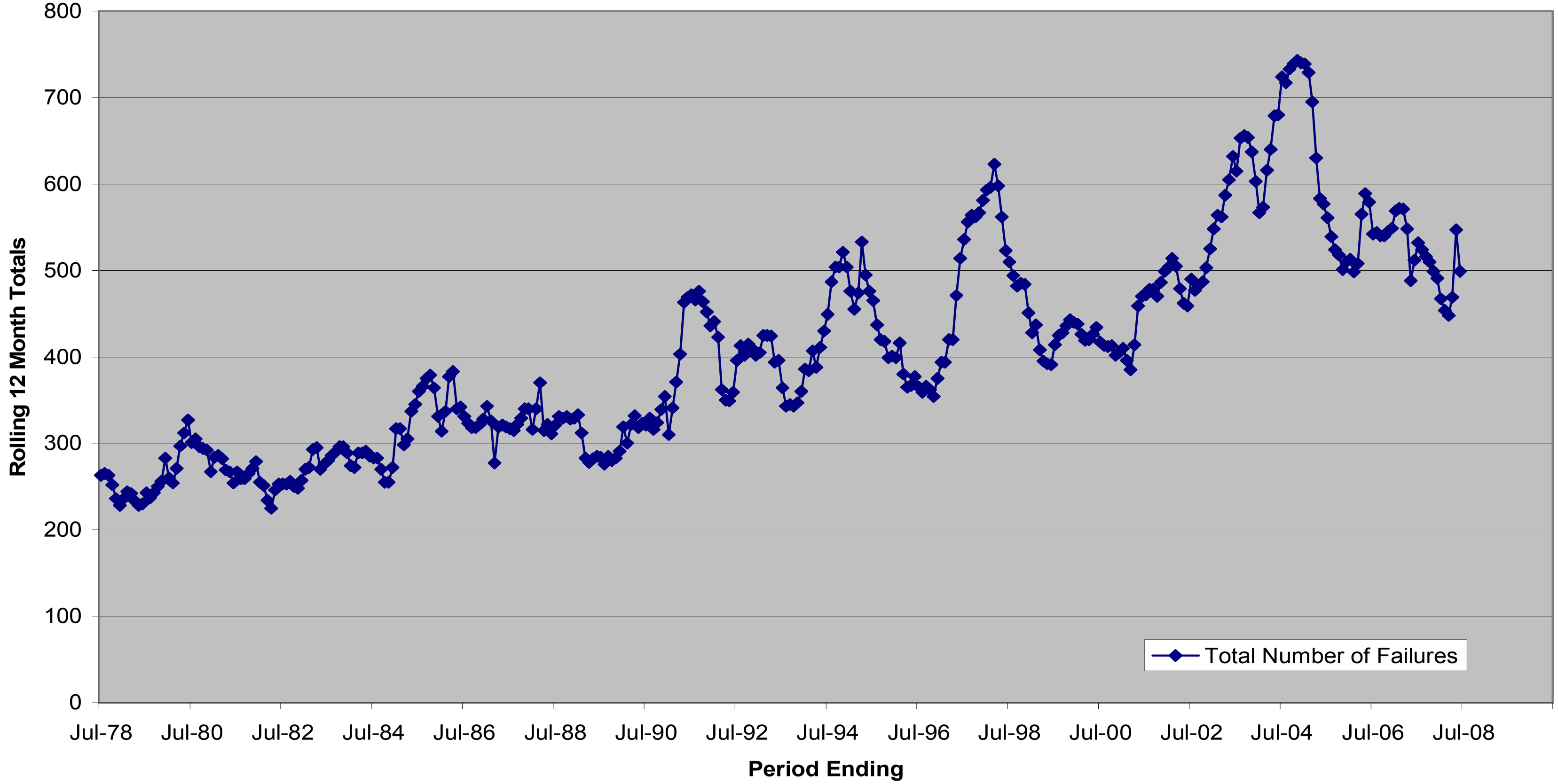

Figure 4.7 - Temporal Distribution of ACT Water Main Failures 1978 - 2008

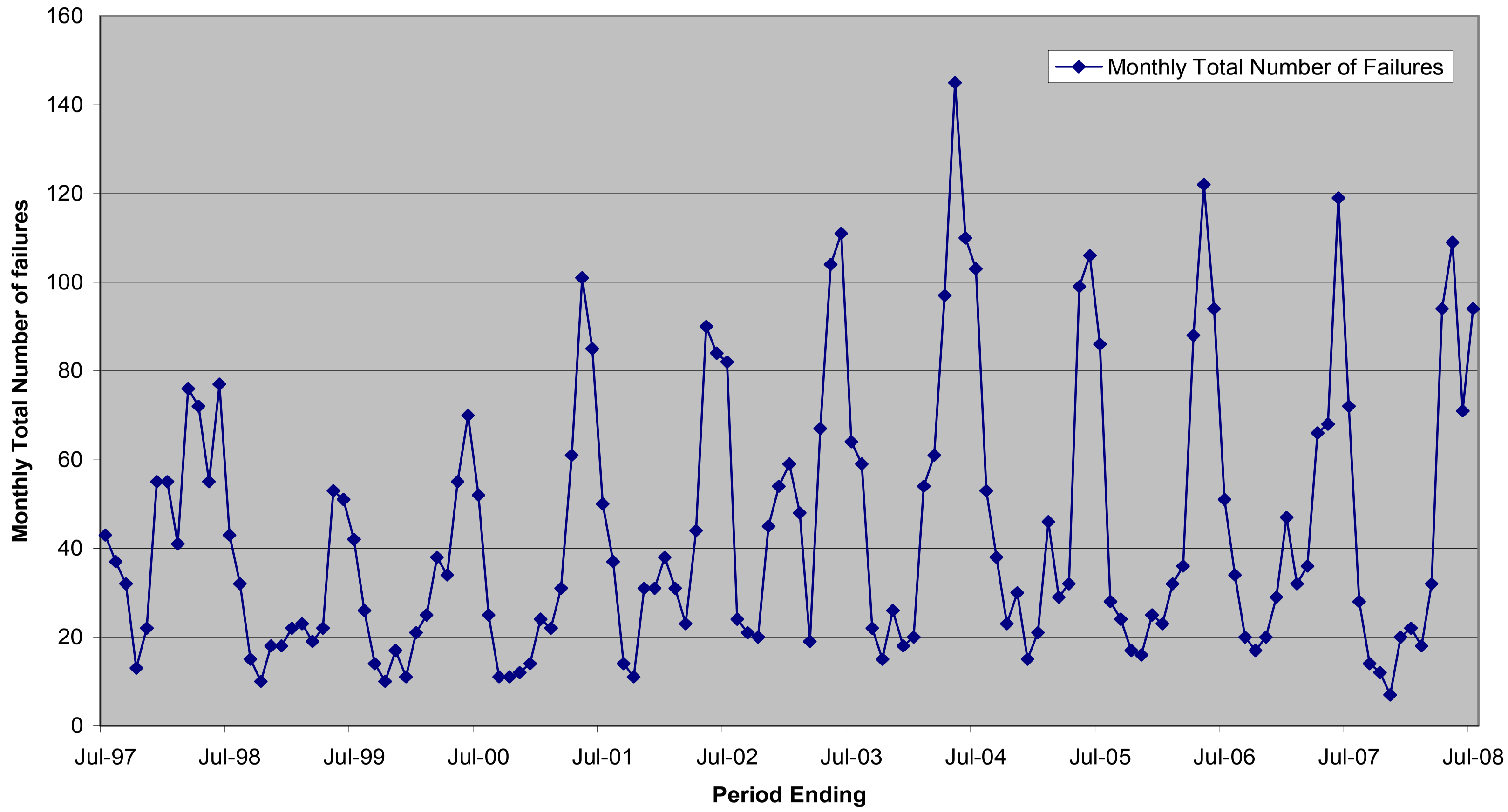

Figure 4.8 – Seasonal Distribution of ACT Water Main Failures 1997 – 2008

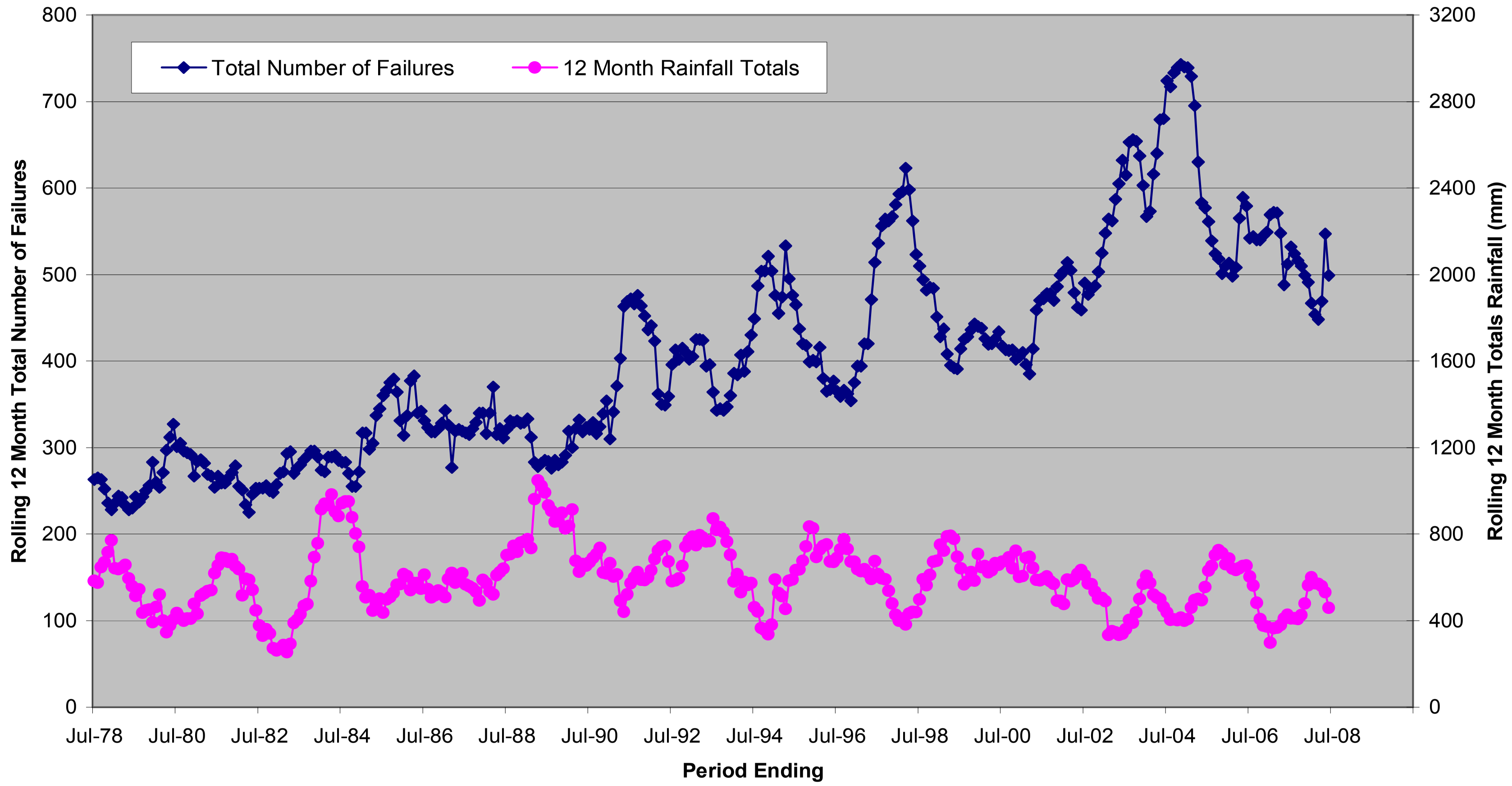

Figure 4.9 - Total Number of Failures versus Rainfall 1978 - 2008

4.6. Future Data Improvements

Failure analysis in the ACT can be greatly improved by compiling all failure records into a central database and incorporating a link to the GIS system and asset databases. This will assist in interrogating data and reporting on water main failures. Data compilation could also include the addition of facility codes for historical records, where available. This would result in existing records becoming more useful.

Another major data improvement that will assist in failure analysis is the incorporation of physical data into the data collection process. This will obviously assist in the development of a physically based water main failure prediction model. The type of physical data that could be collected includes climate data, corrosion pit measurements, soil characteristics such as corrosivity or moisture and pressure readings. Climate data could be collected as a matter of routine, while the other data could be obtained as failures occur. The sooner this physical data starts to be collected, the more data will be available when it is time to begin developing a physical model.

4.7. Chapter Summary

This chapter details the analysis that was carried out on Actew historical water main failure records. The purpose of the analysis was to review the adequacy of existing data, determine factors that explain the type and frequency of failures experienced in the ACT and to identify future data improvements. Key findings of the analysis included the lack of physical data being recorded favouring the development of a statistical model, the influence of climate related factors such as winter and drought on failure rates and the need to expand data collection processes to improve water main failure analysis.

CHAPTER 5

DEVELOPMENT OF A CUSTOMISED WATER MAIN FAILURE PREDICTION MODEL

5. Development of a Customised Water Main Failure Prediction Model

5.1. Introduction

The main objective of this study was to develop a model to describe and predict water main failure rates in the ACT taking into account resource and data limitations.

It is recognised that the development of a failure prediction model is a long term goal that can take many years of data collection and analysis. Many potential model input parameters warrant a study on their own. Also, model validation is a process resulting in ongoing changes and improvements as additional data becomes available. The model proposed by this research constitutes only the beginning of this process.

As highlighted through the literature review, failure prediction models can take many different forms and be of varying levels of complexity. Model type and parameters are usually selected taking into account the purpose of the model, local factors influencing failures, data availability and other limiting factors.

The proposed customised water main failure prediction model to be developed for the ACT must:

- use the most appropriate model type considering available resources
- reflect the actual failure rate in the ACT as accurately as possible taking into account limitations of the study
- incorporate parameters that influence failures in the ACT
- use data that is available or that can be readily obtained.

It should be noted that the customised model is being developed to reflect failure rates in the ACT only. No efforts have been made at this stage to validate the model for other locations. Care should be exercised in using the proposed model for any purposes other than what it was intended for.

5.2. Selection of Model Type and Parameters

Considering the large number of failures in smaller diameter, cast iron water mains installed from the 1960's onwards and the increase of failures in winter and during drought periods, it is evident that a physical model would be of most benefit to Actew. However, available data and resource limitations do not allow for the development of a physical failure prediction model at this time and instead a statistical failure prediction model would be more feasible.

The current failure rate in the ACT does not justify the expense of developing a complex physical model. A statistical failure prediction model is a more cost effective means of analysing and predicting failure trends in the ACT. The statistical model could be used to predict when failures are likely to reach a point where it may be worth considering a physical model and allow time for the physical data to start being collected.

Generally, time is a dominant factor in most statistical prediction models. However, failure analysis shows that time alone is not a good indicator of failure trends. Although failure rates increase over time, cyclical variations also occur. Cyclical variations tend to be caused by climatic influences such as droughts or wet seasons. The large amount of circumferential failures seems to suggest that soil movement and temperature are also influential in failure rates.

Therefore, along with time it is proposed to incorporate some physical parameters into a statistical prediction model to account for cyclical influences caused by frost loads, thermal effects and soil shrink/swell effects. Data and resource limitations prevent the collection of the necessary data to carry out this analysis. However, it may be possible to use climate data as an indicator for these physical parameters. The parameters proposed are rainfall as indicator of soil moisture and ground temperatures as an indicator of the relative harshness of the winter.

5.3. Development of Model

The model described in the following section has been developed using the methods described in Chapter 3. Analysis has been conducted using Microsoft Excel. Additional analysis outputs are shown in Appendix C.

Model 1 – Multi-Variate Regression Model

The first model proposed is a multivariate regression model using total number of failures in a 12 month period as the dependent variable and up to three independent variables including time, soil moisture and ground temperature. This is similar to a multivariate regression model proposed by Kleiner and Rajani (2000a) which uses rain deficit and frost index as explanatory variables.

Available input parameters include time (month), rainfall (rolling 12 month totals) and ground temperatures (rolling 12 month total number of days in a month where ground temperature was equal to or less than -1°C). Only variables that significantly improve the accuracy of the model will be included in the model.

The model will be developed using rolling twelve month failure totals for the period from July 1978 to June 2008. The time step used in the model is 1 month and therefore the sample size used in developing the model is 360.

Correlation

The first step in the development of the model was determining the correlation between the dependent and explanatory variables. Correlation analysis was carried out in Microsoft Excel and a copy of the correlation matrix for this analysis is shown in Figure 5.1.

Table 5.1 Correlation Matrix for Variables for Model 1

	No Of Failures	*Time*	*Rain*	*Temp*
No Of Failures	1			
Time	0.862047711	1		
Rain	-0.340968677	-0.10655	1	
Temp	0.19501653	0.058149	-0.58751	1

Looking at the matrix it can be seen that time (0.862) has the strongest correlation with the dependent variable followed by rainfall (-0.341) and ground temperature (0.1950). Correlation between the independent variables are relatively low except for the correlation between rain and temperature (-0.588) which is significant.

Variable 1

The first explanatory variable included in the model was time because of its high correlation with the dependent variable. Previous studies had shown time to be a relatively good predictor of water main failures but also suggested that failures rates tended to display an exponential relationship with time. Tests were conducted to determine if this was the case in the ACT also. This was done by fitting trends to failure plots over time.

Analysis of the failure plot confirmed that the best fit to the data was an exponential trend with equation shown in Figure 5.1. The fitted exponential trend and coefficient of determination are illustrated in Figure 5.2. The exponential trend appears to account for 79.8% of the variation in number of failures.

Figure 5.1 Exponential Time Relationship with Failures

$$Y = 247.3e^{0.0025X}$$

Regression analyses of failures vs. time (linear) and failures vs. time (exponential) were also conducted in Microsoft Excel to compare the results. Regression statistics showed that linear model was able to account for 74.2% of variation in the number of failures as opposed to 73.7% from exponential model. While the linear relationship appeared to give slightly better results, residual plots showed that the exponential relationship had the better fit.

Due to the slightly better fit, the exponential relationship has been included in the model. For the rest of this study, time will be transformed by the equation shown in Figure 5.1 before being applied in subsequent regression analyses.

Variable 2

As discussed previously, additional variables were only to be included in the model if they resulted in a significant improvement to the model. This meant for another variable to be added to the model the adjusted coefficient of determination had to improve significantly from 0.737. A partial F-test with a significance level of 0.05 was to be used to assess the significance of any additional variables.

Both remaining explanatory variables had moderate correlation with the dependent variable. Rainfall had the higher correlation and so was the obvious choice to be included next in the model. However, partial F tests have been conducted for both variables.

Partial F-tests were performed using Microsoft Excel. The results for rainfall are summarised in Table 5.2. Using a significance level of 5% with 1 and 357 degrees of freedom the critical F value is 3.84. From Table 5.2 it can be seen that the calculated F value of 1105.63 is greater than the critical value of 3.84. Therefore the inclusion of rainfall in the model significantly contributes to the improvement of the model.

Table 5.2 Partial F-Test for including Rainfall in a Model already including Time

Source	df	Sums of Squares	Mean Square (Variance)	F
Regression	2	4081680.392	2040840.196	
X_2	1	605045.851	605045.851	
X_2/X_1	1	3476634.541	3476634.541	1105.627
Error	357	1122583.597	3144.491869	
Total	359	5204263.989		

where X_1=time and X_2 = rainfall

The results for the partial F-Test for ground temperature are summarised in Table 5.3. The F value of 1044.03 is also greater than the critical F value of 3.84 and it can be concluded that the inclusion of ground temperature will also significantly improve the model.

Table 5.3 Partial F-Test for including Ground Temperature in a Model already including Time

Source	df	Sums of Squares	Mean Square (Variance)	F
Regression	2	3928588.697	1964294.348	
X_3	1	197925.6904	197926.6904	
X_3/X_1	1	3730663.006	3730663.006	1044.033
Error	357	1275675.292	3573.320146	
Total	359	5204263.989		

where X_1 =time and X_3 = ground temperature

Although the partial F-tests showed that either variable would improve the model, regression analysis showed that including rainfall would improve the accuracy of the model from 73.7% to 78.3% as opposed to 75.4% for a model including ground temperature. Rainfall, therefore, was selected as the second explanatory variable in the model.

Variable 3

Similar procedures were used to assess the benefits of adding a third variable to the model. The critical F value for a significance level of 5% with 2 and 356 degrees of freedom is 3.00. The partial F-test for the significance of adding ground temperature to a model with time and rainfall is shown in Table 5.4. Clearly the F value of 0.05 is below the critical F value and adding ground temperature to the model will not significantly improve its accuracy. Therefore, ground temperature will not be included in the model.

Table 5.4 Partial F-Test for including Ground Temperature in a Model already including Time and Rainfall

Source	df	Sums of Squares	Mean Square (Variance)	F
Regression	3	4081841.652	1360613.884	
X_3	2	4081680.392	2040840.196	
X_3/X_{12}	2	161.2602876	161.2602876	0.051147
Error	356	1122422.337	3152.871733	
Total	359	5204263.989		

where X_{12} =time + rainfall and X_3 = ground temperature

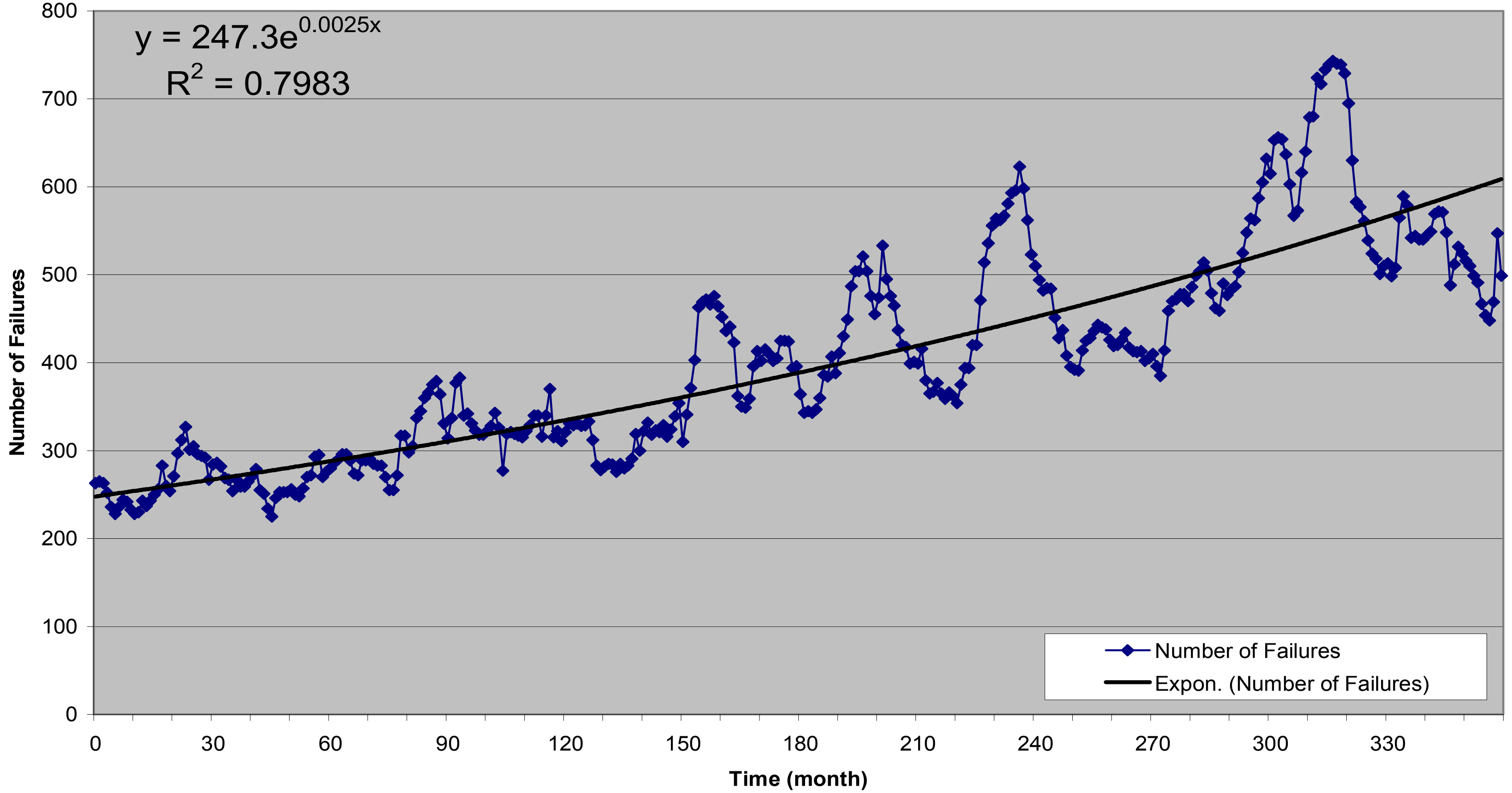

Figure 5.2 Line of Best Fit for ACT Water Main Failures 1978 - 2008

Discussion of Model

The proposed model is a two variable regression model with time and rainfall as the explanatory variables.

The model is of the form:

$$\textbf{Total Number of Failures} = 123.997 + 237.33e^{0.0025X_1} - 0.175X_2$$

where x_1 = time (month)

x_2 = rainfall (mm)

Figure 5.3 shows a comparison between predicted failures using the model and actual failures over the period from 1978 to 2008. The model seems to have a fair correlation with the actual failure rate. Although the model is not accurate at predicting the magnitude of cyclical variations, it does seem to be able to predict their occurrence.

Regression analysis for the proposed model is shown in Figure 5.4. From the summary output it can be seen that time and rainfall is able to account for approximately 78% of the variation in the total number of failures. This result is promising considering that only two variables have been used in the model out of the many that influence water main failures.

Residuals plots (shown in Figures 5.5 and 5.6) display an unequal variance in the distribution of residuals and a strong cyclical trend. In Figure 5.5 the spread of residuals appears to be increasing as the number of failures increases. Figure 5.6 shows a cyclical trend, or autocorrelation, in the distribution of residuals. These findings violate some of the assumptions of regression analysis in regard to homoscedasticity (or the constancy of residuals) and the independence of residuals. This raises some concerns over the validity of the model and suggests that there may be some other effects that are not accounted for in the model. This is quite probable considering the number of factors that can influence water main failures.

One possible explanation for the autocorrelation effect may be limitations with the data used in the model. Firstly, some moderation of data was required to account for periods where data was incomplete or missing. Failures during these periods were moderated to reflect failure rates for periods where complete data was available. This could quite possibly have biased the results. Secondly, because 12 month rolling totals of failures and rainfall were taken only one month apart there is always going to be some inherent correlation from one data point to the next. Successive readings are not independent of each other.

Partial regression plots for time (Figure 5.7) and rainfall (Figure 5.8) show a moderate positive linear relationship between time and failures and a weak negative linear relationship between time and rainfall. This meets the assumption of linearity in regression analysis.

Overall the model as it is appears to give creditable results. However, the effect of autocorrelation raises some issues and further investigations will need to be carried out. There is also scope for trying to add other variables as more data becomes available. In hindsight ground temperatures and rainfall were too closely correlated to each other to be both included in the model. Independent variables need to independent of each other.

Improvements to the Model

While the proposed model appears to provide a fair prediction of the failure rate in the ACT for the period from 1978 to 2008, further analysis raises a number of issues regarding the validity of the fitted model. Before the model can be accepted for use further investigations are required to understand and account for these issues if possible. Some of the possible actions that may be taken are outlined below.

- Use the model as it is recognising that model accuracy could possibly be improved.
- Determine if linearity can be improved by transformation of model variables.
- Determine if additional explanatory variables can be used in the model to explain residual trending effects.
- Determine if autoregressive modelling techniques can be incorporated into the model to take advantage of the autocorrelation effects.
- Determine if the autocorrelation effect can be overcome by increasing the time interval between data points from one month to one year.

Time limitations did not allow for all of these options to be investigated as part of this study. Therefore, it was decided to concentrate on determining if the regression model could be improved by increasing the time step in the model from one month to one year.

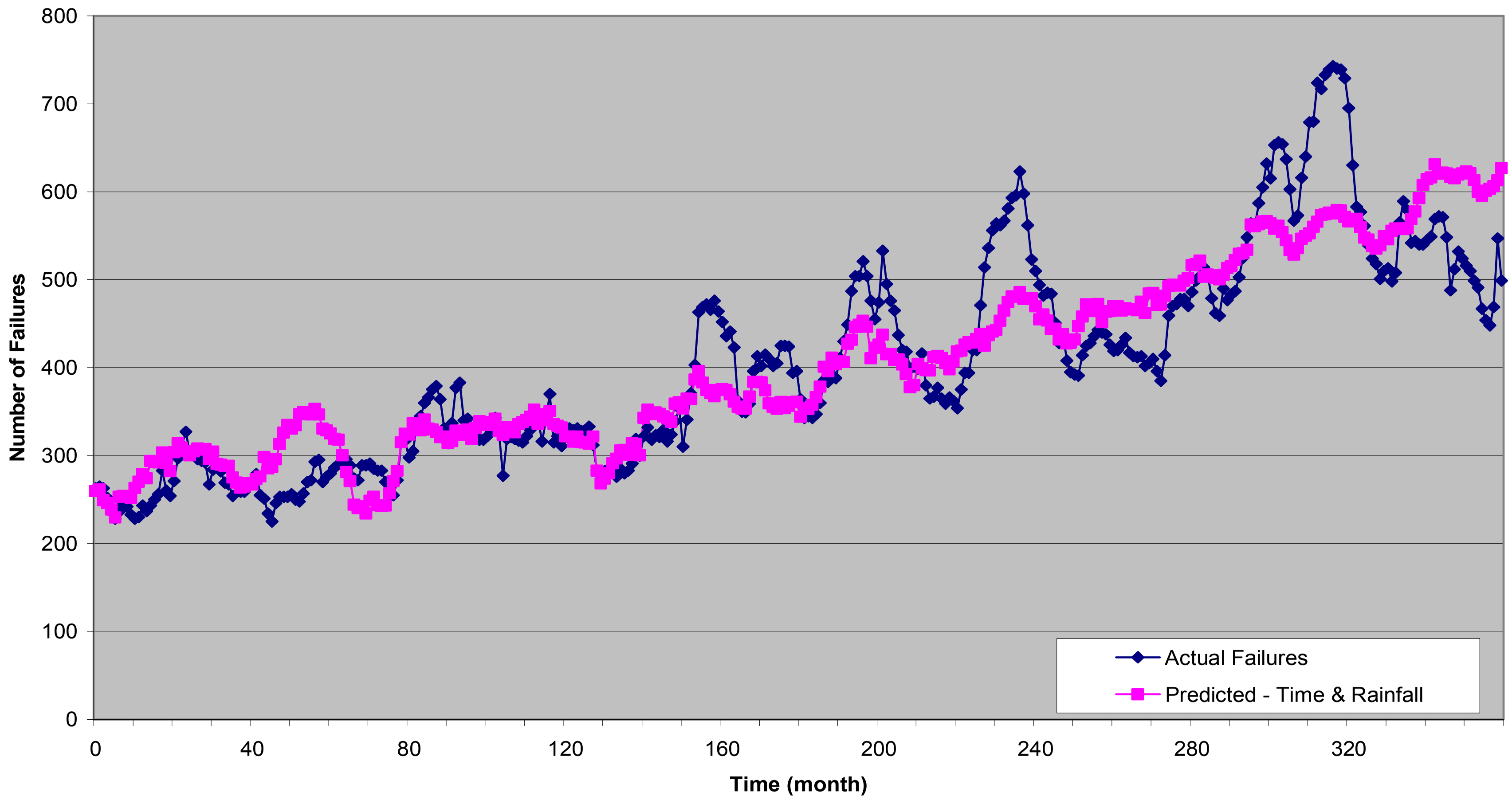

Figure 5.3 Comparison of Predicted versus Actual Failures for the ACT 1978 - 2008

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.885604548
R Square	0.784295416
Adjusted R Square	0.783086987
Standard Error	56.075769
Observations	360

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	4081680.392	2040840.196	649.0207	1.2414E-119
Residual	357	1122583.597	3144.491869		
Total	359	5204263.989			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	123.9970425	17.98575791	6.894179446	2.47E-11	88.62569104	159.368394	88.62569104	159.3683939
X Variable 1	0.961318398	0.028910991	33.25096718	2.3E-111	0.904461144	1.01817565	0.904461144	1.018175653
X Variable 2	-0.175416388	0.020010064	-8.766408221	7.62E-17	-0.214768802	-0.136064	-0.21476880	-0.136063973

Figure 5.4 Regression Analyses for Failure Prediction Model 1

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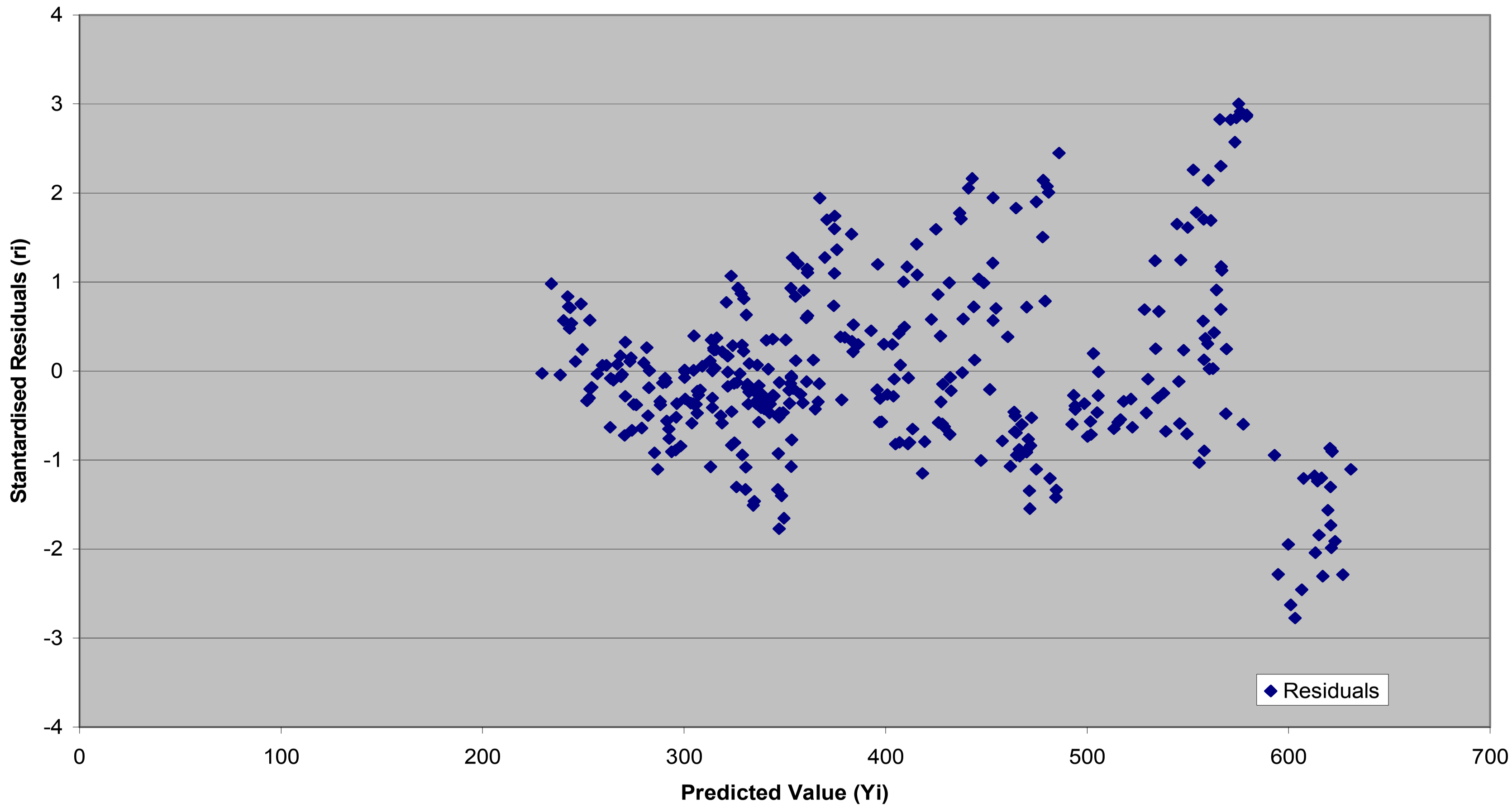

Figure 5.5 Standardised Residuals versus Predicted Value (Y_i)

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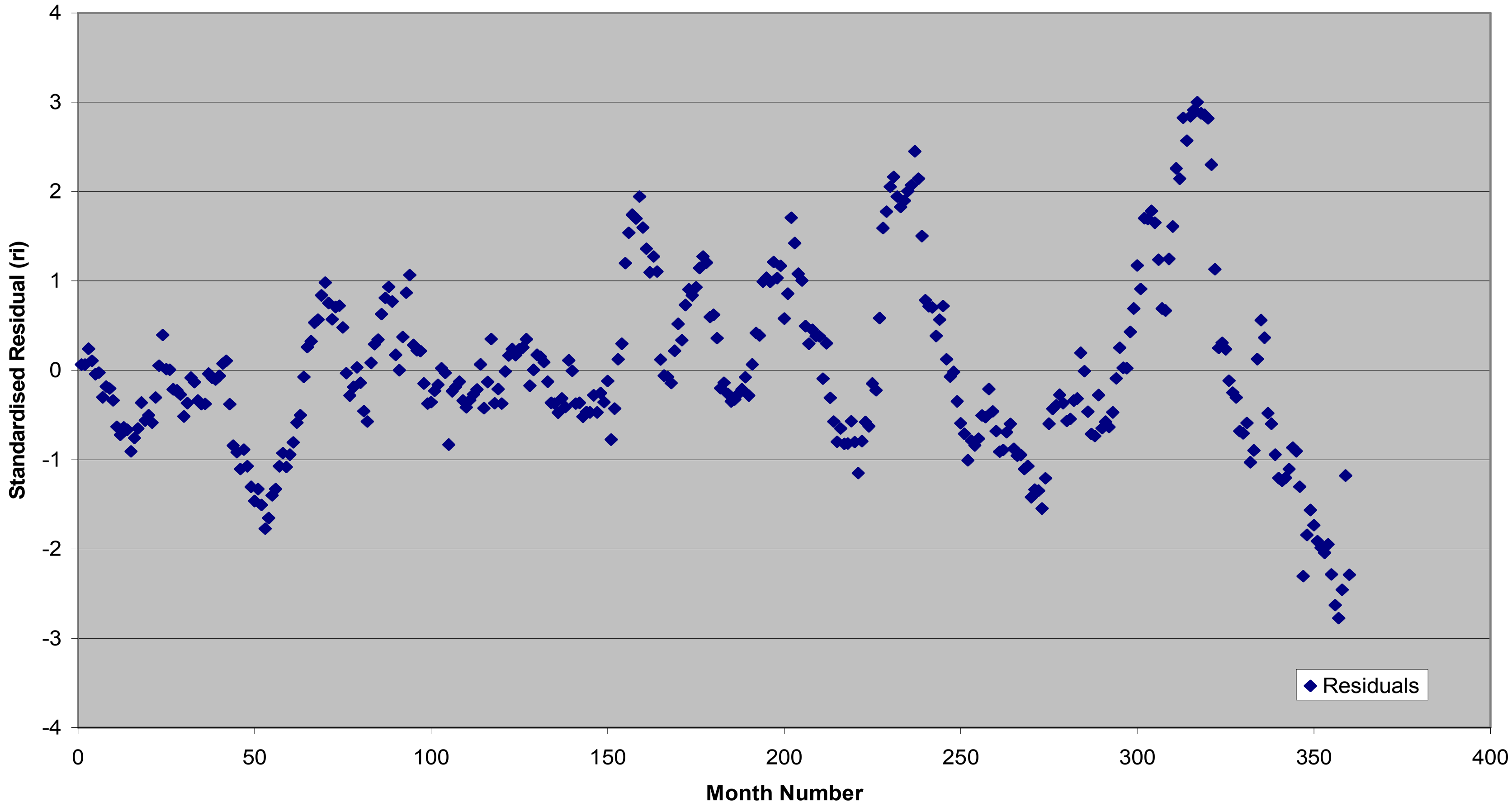

Figure 5.6 Standardised Residuals Plotted in Sequential Order

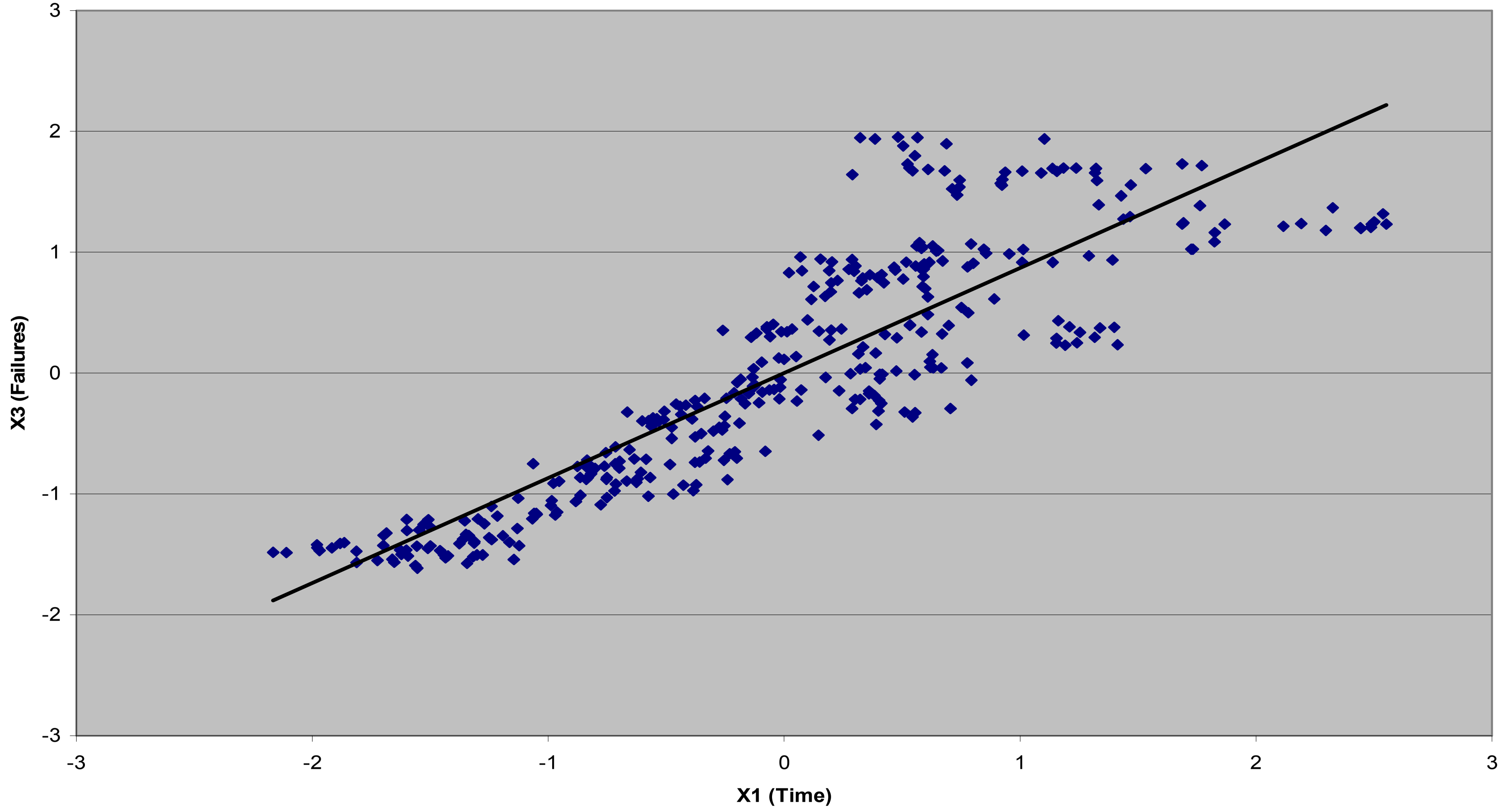

Figure 5.7 Partial Regression Plot of Failures versus Time

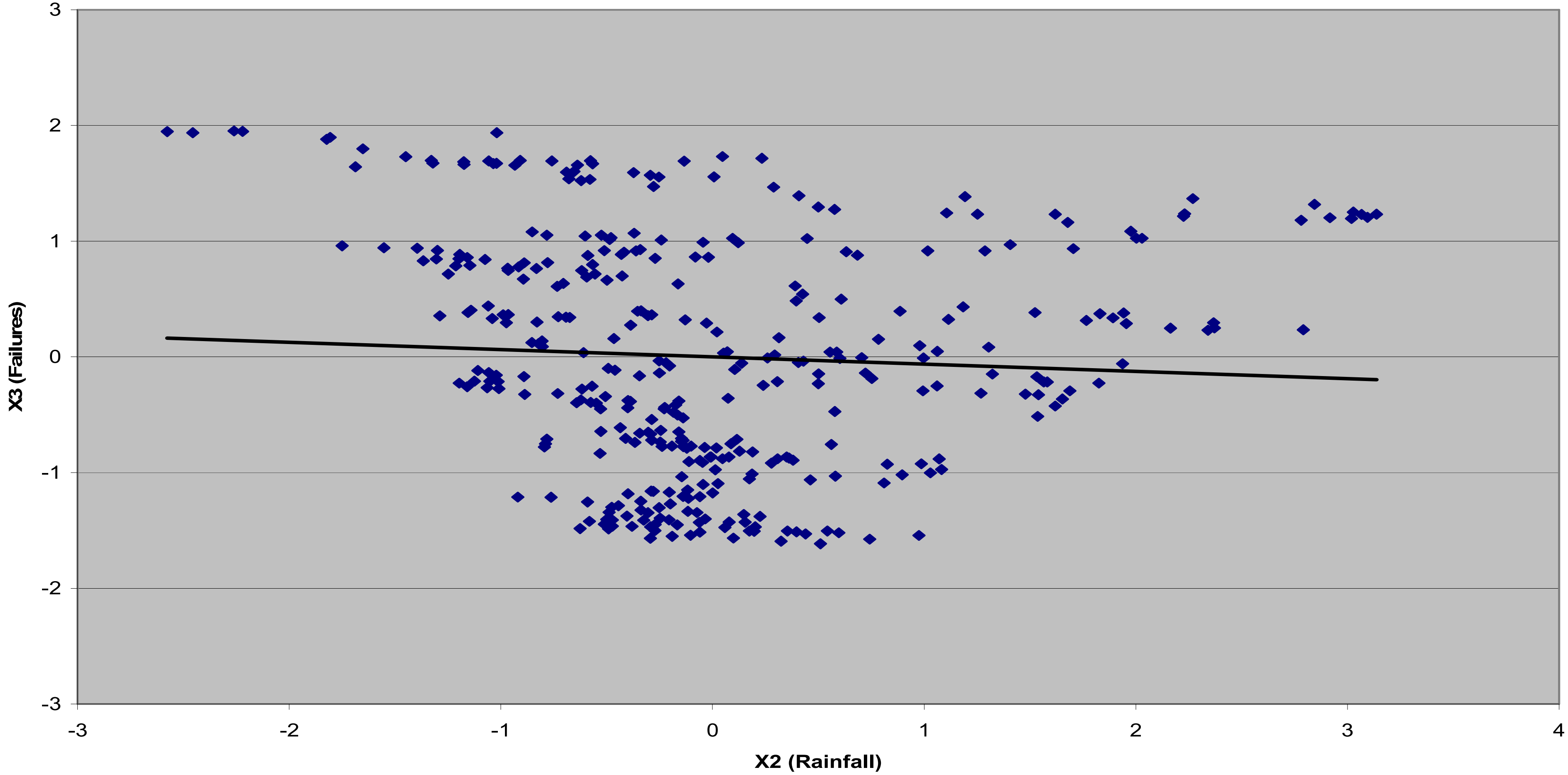

Figure 5.8 Partial Regression Plot of Failures versus Rainfall

Model 2 – Multi-Variate Regression Model

The second model proposed was of a similar form to the first model and used the same procedure to develop. The major difference between the two models is that the time step has been increased to 1 year from 1 month. This means the sample size is now 30 and independent twelve monthly totals are now being used instead of rolling twelve month totals. The aim of this was to see if this reduced the autocorrelation effect.

Correlation

Table 5.5 shows the correlation matrix for Model 2. The results are similar to Model 1. Time has a high positive correlation with the dependent variable, followed by rain with a moderate negative correlation and ground temperature with a weak positive correlation. Correlation between time and the other independent variables is relatively low, while correlation between rainfall and ground temperature is moderately high. Once again time is the obvious choice as the first variable to be included in the model.

Table 5.5 Correlation Matrix for Variables for Model 2

	Failures	*Time*	*Rain*	*Temp*
Failures	1			
Time	0.850211	1		
Rain	-0.38363	-0.12724		
Temp	0.108427	0.061192	-0.4934	1

Variable 1

The first explanatory variable included in the model was time. Following a similar process as for Model 1 it was determined that an exponential time relationship was to be used in the model. Figure 5.9 shows the fitted exponential trend, equation and the coefficient of determination.

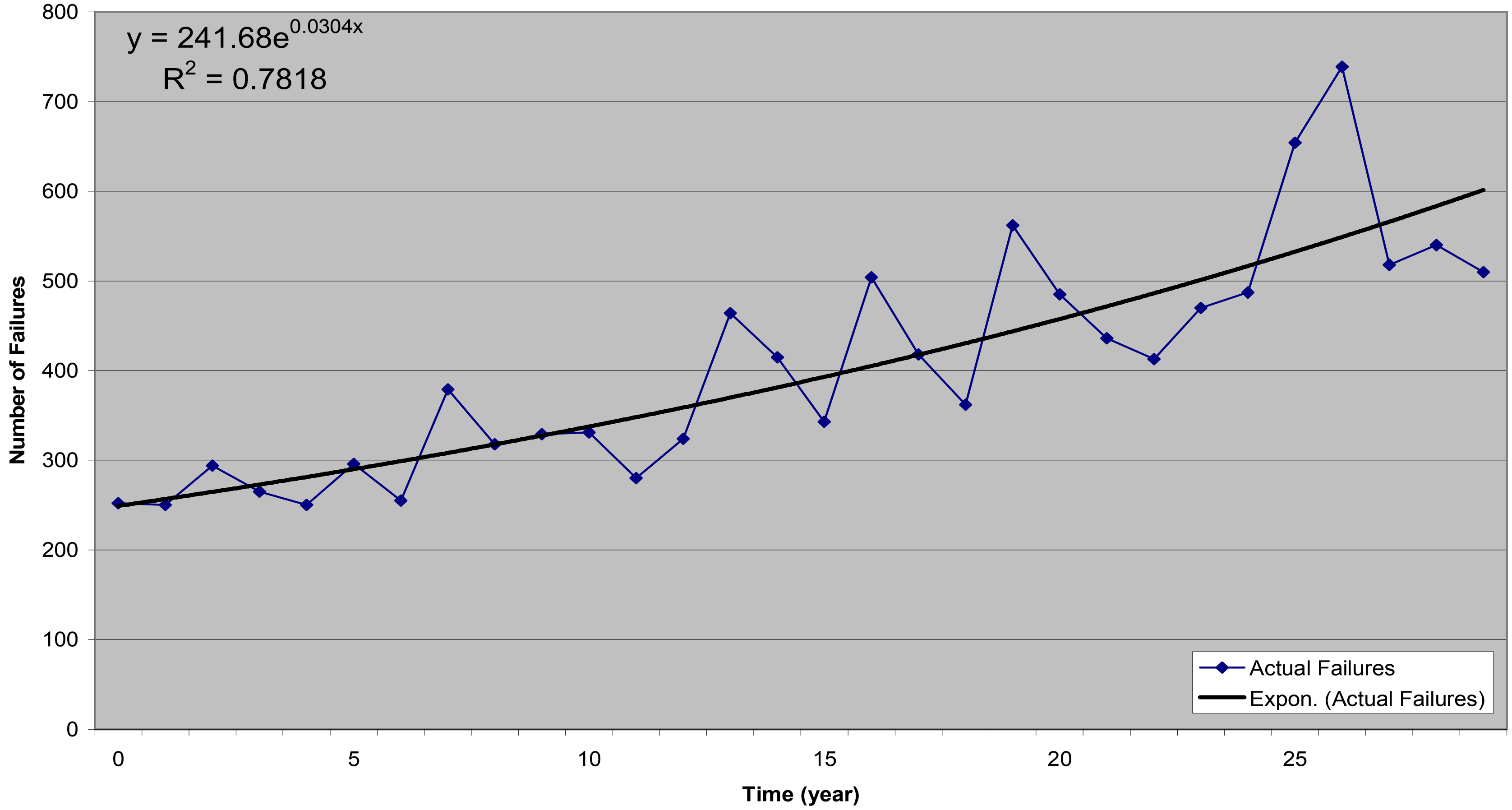

Figure 5.9 Line of Best Fit for ACT Water Main Failures 1978 - 2008

<u>Variable 2</u>

Once again partial F-tests were conducted to determine if the inclusion of rainfall or ground temperature would significantly improve the model. Results for the tests are shown in Tales 5.6 and 5.7. The critical F value for a model with 1 and 27 degrees of freedom and significance of 5% is 4.21. Inclusion of rainfall in the model will significantly improve the model while inclusion of ground temperature will not.

Table 5.6 Partial F-Test for including Rainfall in a Model that already includes Time

Source	df	Sums of Squares	Mean Square (Variance)	F
Regression	2	355398.6073	177699.3037	
X_2	1	329425.886	329425.886	
X_2/X_1	1	25972.72137	25972.72137	6.882773
Error	27	101886.7593	3773.583679	
Total	29	457285.3667		

where X_1 =time and X_3 = rainfall

Table 5.7 Partial F-Test for including Ground Temperature in a Model that already includes Time

Source	df	Sums of Squares	Mean Square (Variance)	F
Regression	2	330246.6692	165123.3346	
X_3	1	329425.886	329425.886	
X_3/X_1	1	820.783259	820.783259	0.174444
Error	27	127038.6974	4705.136942	
Total	29	457285.3667		

where X_1 =time and X_3 = ground temperature

Variable 3

Due to the high correlation between rainfall and ground temperatures, inclusion of both ground temperature and rainfall in the model was unlikely to significantly improve the model. This was confirmed by the partial F-test shown in Figure 5.8. The critical F value for a model with 1 and 26 degrees of freedom and significance of 0.05 is 4.23. The calculated F value is well below the critical value and therefore inclusion of the third variable is not significant and will not be included in the model.

Table 5.8 Partial F-Test for including Ground Temperature in a Model that already includes Time and Rainfall

Source	df	Sums of Squares	Mean Square (Variance)	F
Regression	3	4081841.652	1360613.884	
X_3	2	4081680.392	2040840.196	
X_3/X_{12}	2	161.2602876	161.2602876	0.051147
Error	26	1122422.337	3152.871733	
Total	29	5204263.989		

where X_{12} =time and rainfall and X_3 = ground temperature

Discussion of Model 2

Model 2 is also a two variable regression model with time and rainfall as the explanatory variables.

The model is of the form:

$$\textbf{Total Number of Failures} = 145.259 + 241.68e^{0.0304X_1} - 0.206X_2$$

where x_1 = time (year)

x_2 = rainfall (mm)

Figure 5.10 shows a comparison between predicted failures and actual failures over the period from 1978 to 2008. Correlation with the actual failure rate is fairly high. The difference between predicted and actual failures appears to be increasing over time as the total number of failures increases.

Regression analysis for the proposed model is shown in Figure 4.10. From the summary output of this analysis it can be seen that time and rainfall is able to account for approximately 76% of the variation in the total number of failures. This is similar to that for Model 1.

Although not as noticeable, the residual plots for Model 2 (shown in Figures 5.12 and 5.13) display similar effects to Model 1. The spread of residuals appears to be increasing as the number of failures increases and a cyclical trend, or autocorrelation, in the distribution of residuals is evident.

Partial regression plots meet the assumption of linearity. Figure 5.14 shows a strong positive linear relationship between time and failures and Figure 5.15 a weak negative linear relationship between rainfall and failures.

<u>Discussion of Results</u>

Although basic and using only two explanatory variables, the two proposed models appear to give fairly accurate results. Model 1 was able to explain approximately 78% of the variation in failure rates, while Model 2 was able to explain approximately 76%.

Analysis of the two models identified some issues relating to autocorrelation and an increase in residual variance as the number of failures increase. This raises concerns about the validity of the model and suggests further investigations may be necessary to determine the cause of these effects.

Data limitations also need to be considered. Confirmed and reliable data covering the entire network is only available from July 1997 with data moderation being required to cover other periods where the data was missing or incomplete. This data moderation may have biased the results. Variation between predicted failures and actual failures appears to be increasing especially for the period since 1997. Further validation is required before an accurate assessment can be made of the model.

The other thing that needs to be considered is that the two models are both statistical models and therefore cannot be used for condition based predictions. The cost and time required to improve these models may be better spent in the development of a physically based failure prediction model.

This being the case it may be possible to accept the models as they are until a physical model is developed. Even if the models were able to achieve perfect correlation with past failure history, to make future predictions rainfall totals still need to be predicted also. However, a model of this sort would still be useful in predicting failure trends to account for predicted droughts or wet seasons.

5.4. Chapter Summary

This chapter has provided a description of the development of two customised multivariate water main failure prediction models taking into account limitations in existing Actew water main failure records. Both models use time (Model 1 - month and Model 2 - year) and rainfall (12 month totals – mm) to predict total number of failures. Preliminary results are promising but further testing and validation is required.

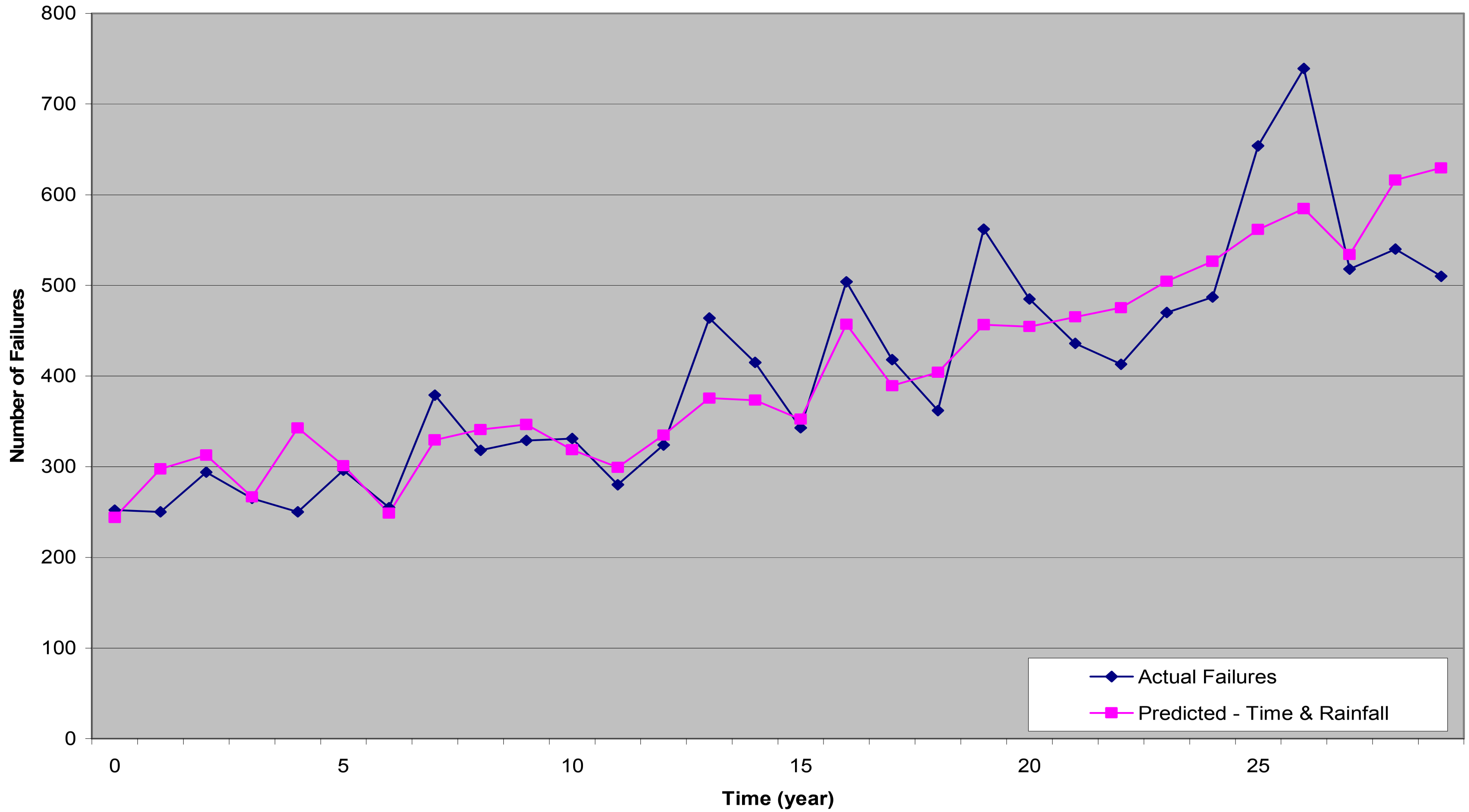

Figure 5.10 Comparison of Predicted versus Actual Failures for the ACT 1978 - 2008

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.881585034
R Square	0.777192172
Adjusted R Square	0.760687888
Standard Error	61.4295017
Observations	30

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	355398.6073	177699.3037	47.09033	1.5742E-09
Residual	27	101886.7593	3773.583679		
Total	29	457285.3667			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	145.2588971	69.83287662	2.080093276	0.047137	1.973671436	288.5441228	1.973671436	288.5441228
X Variable 1	0.980004697	0.112159262	8.737617201	2.36E-09	0.749872903	1.210136491	0.749872903	1.210136491
X Variable 2	-0.20607374	0.078549047	-2.62350403	0.01414	-0.36724307	-0.04490441	-0.36724307	-0.04490441

Figure 5.11 Regression Analyses for Failure Prediction Model 2

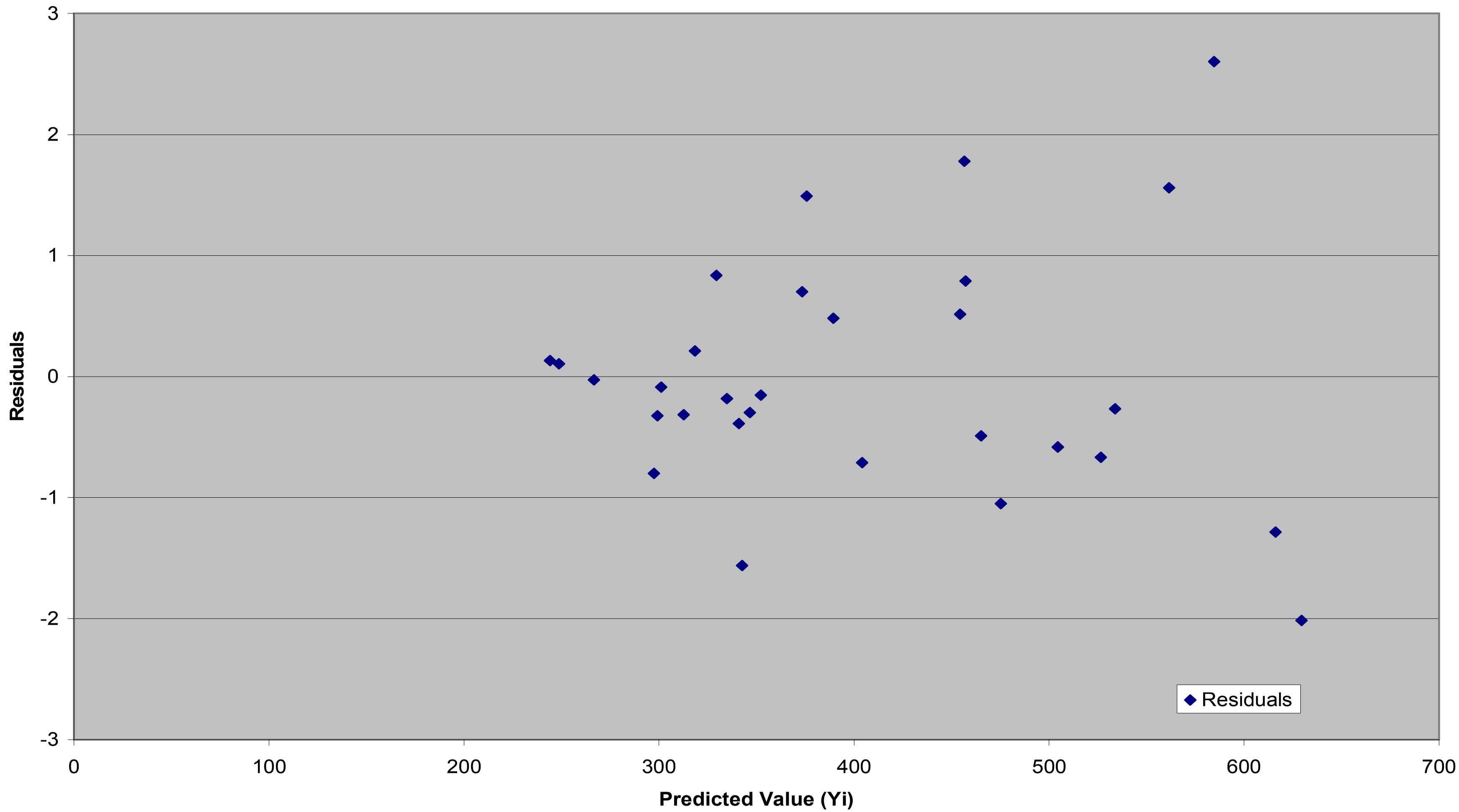

Figure 5.12 Standardised Residuals versus Predicted Value (Y_i)

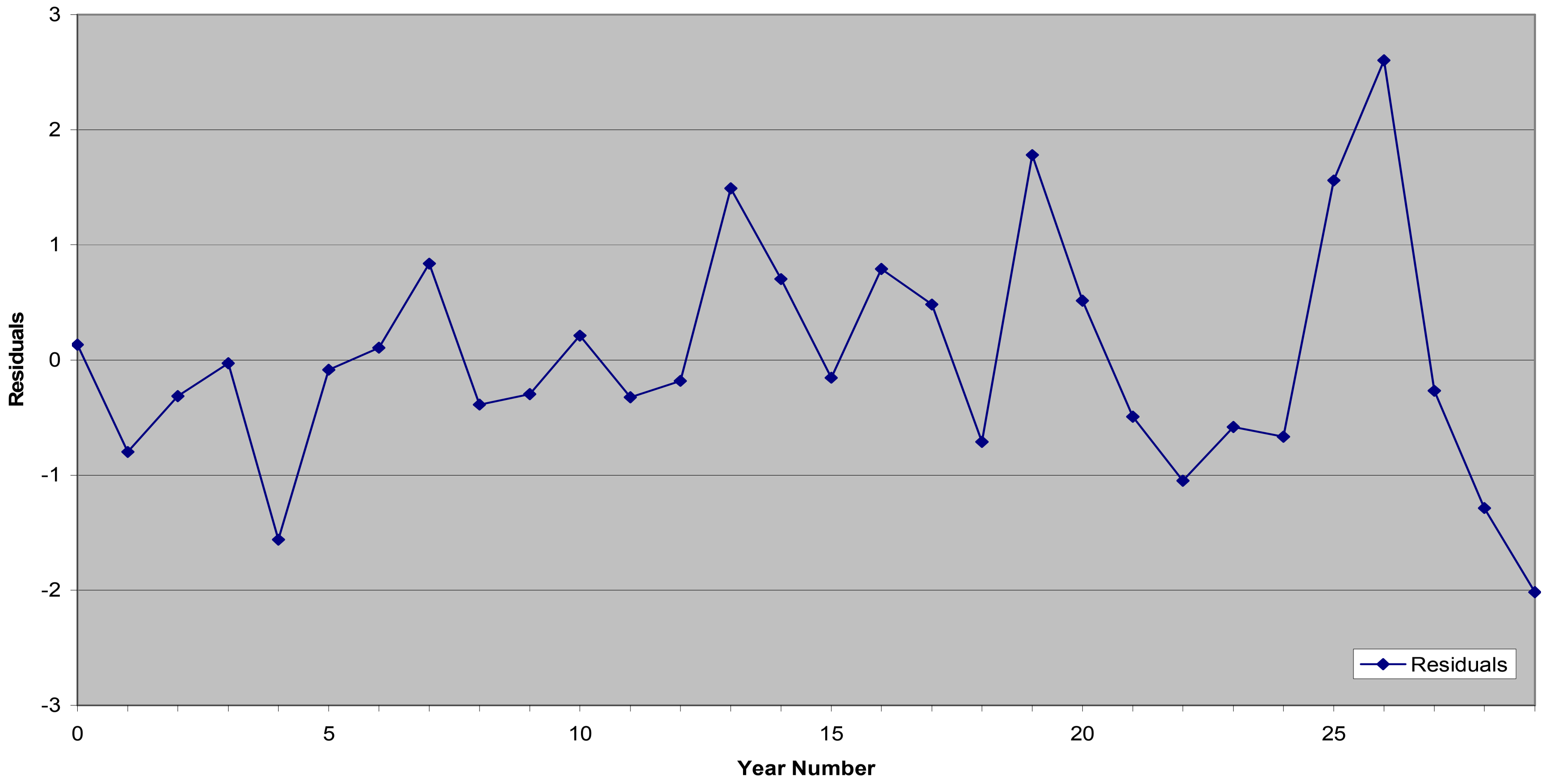

Figure 5.13 Standardised Residuals Plotted in Sequential Order

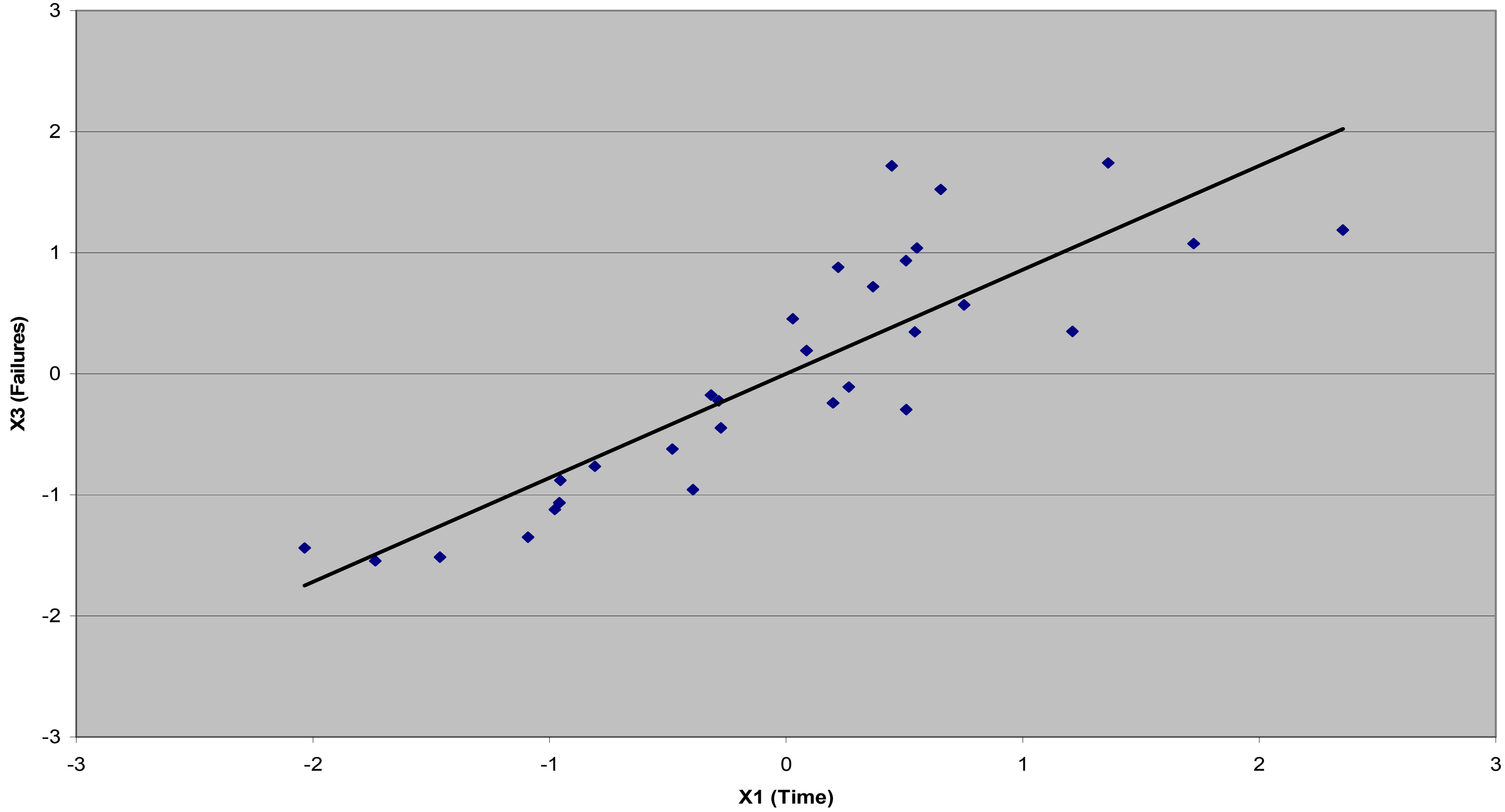

Figure 5.14 Partial Regression Plot of Failures versus Time

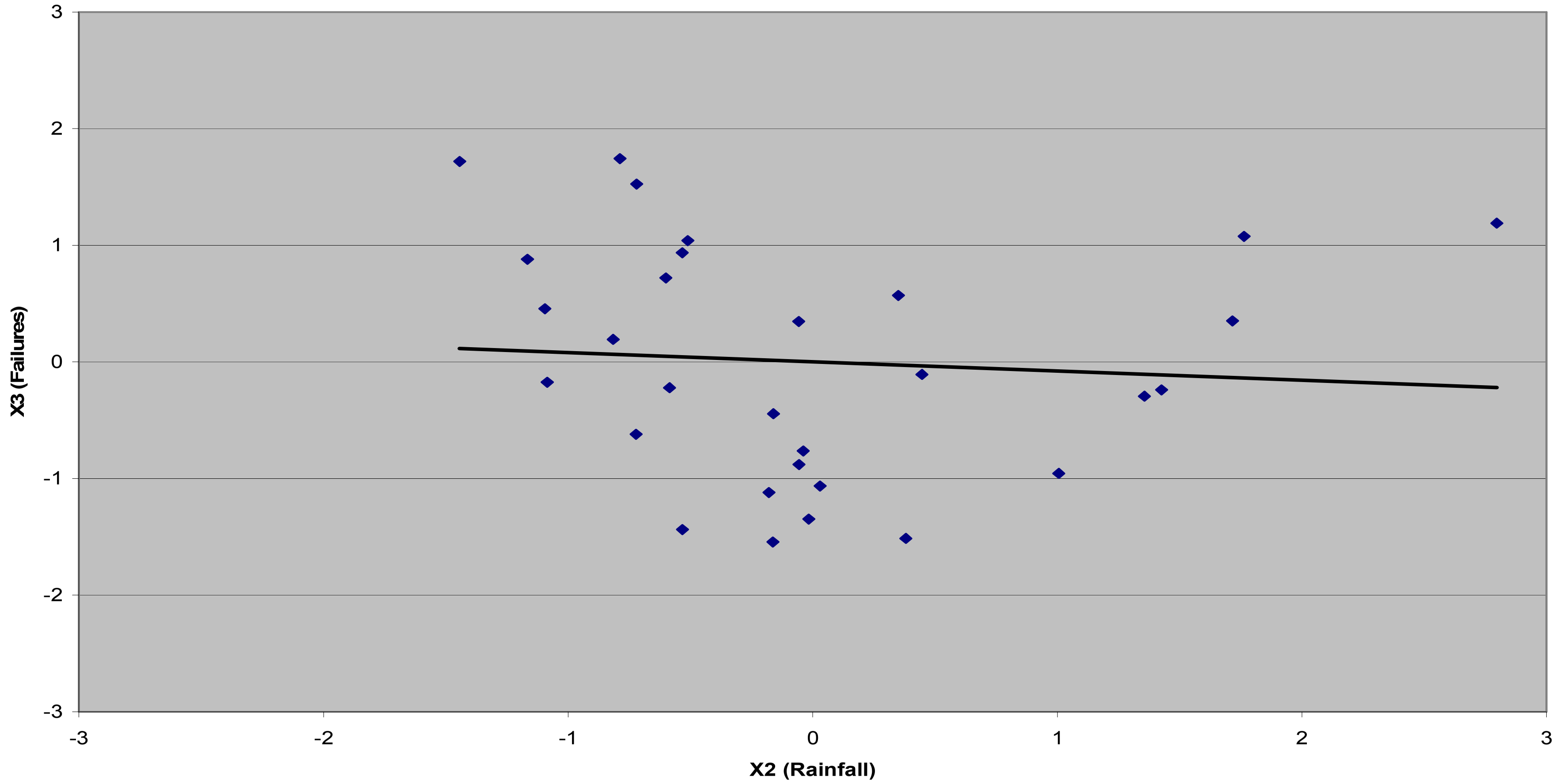

Figure 5.15 Partial Regression Plot of Failures versus Rainfall

CHAPTER 6

COMPARISON OF PROPOSED MODELS WITH EXISTING FAILURE PREDICTION MODELS

6. Comparison of Proposed Models with Existing Failure Prediction Models

The objective of the following chapter is to compare the models proposed in the previous chapter to some of the existing failure models discussed in the literature review. Comparison will be made by looking at how well the models achieve their objectives, the input variables used in the models, different types of model output and model accuracy.

6.1. Purpose

This study has highlighted a number of different types of water main failure prediction models of varying levels of complexity. These range from simple univariate statistical prediction models to multivariate physically based models. Most would consider physically based models the ultimate in failure prediction and therefore superior to the other model types. This may be the case. However, a model should be assessed on how well it meets its intended function and not on how complex the method it uses.

The two basic prediction models proposed by the study may be limited in the information they can provide, but they meet specifications. That is the model type is appropriate for the available resources, reflects the actual failure rate in the ACT as accurately as possible taking into account limitations of the study, incorporates parameters influencing failures in the ACT and uses data that is available or can be readily obtained. Therefore, it can be said that the proposed models are fit for purpose.

6.2. Input Variables

Studies have shown that a number of factors influence water main failures and can be used in failure prediction models. Some of these include time, corrosion pit depths, soil loads, rain deficits and freezing index. Physical models aim to incorporate as many of these factors as possible in order to improve model accuracy. Statistical models on the other hand, seek to make the most efficient use of available data and variables will be omitted if they don't significantly add to the model. The two proposed models use only two out of three possible variables. The inclusion of ground temperature did not significantly add to the accuracy of the model in this case. Perhaps as more data becomes available additional explanatory variables that do improve the model may be included.

6.3. Model Output

The use of failure prediction models are influenced by the type of output produced by the model. For example, physically based prediction models are able to predict time until failure based on actual pipe conditions and local environmental influences. These models are suitable for use in decision making processes to determine when individual pipes should be replaced instead of just being repaired. Statistical models identify trends in historical data and assume these continue into the future. Like the two models developed in the study, output is usually total number of failures for a given time period. Statistical models are suitable for monitoring system performance and assisting in planning processes including resource allocation.

6.4. Model Accuracy

Model accuracy is probably the hardest thing to compare between models. Most models have been customised to suit a particular location. Different model types have different outputs. Even if a model uses similar methods results are influenced by the quality of the data used in the model.

The literature review looked at a number of statistical failure models proposed by others including Kleiner and Rajani (2000a and 2002) and Achim et al (2007). These studies mention models achieving coefficients of determination ranging from 0.23 to 0.86. The models in this study achieved coefficients of determination of 0.78 for Model 1 and 0.76 for Model 2. This compares well with the results of other studies. Of course there are a number of other factors that need to be taken into account when assessing the accuracy of these models and further validation is required.

6.5. Chapter Summary

This chapter outlined some of the difficulties in making comparisons between failure prediction models because of the different methods used and the development of models to suit specific applications. The two customised models developed in this study, although basic, meet specifications and seem to compare well with similar existing models. Further testing and validation is required before any results can be accepted.

CHAPTER 7

CONCLUSION AND RECOMMENDATIONS

7. Conclusions and Recommendations

7.1. Conclusions

The purpose of this study was to investigate water main failures in the ACT in order to develop a customised water main failure prediction model that could be used to monitor system performance and assist in developing replacement and renewal strategies. The customised model was to incorporate findings from the literature review and take into account factors that were shown to influence failures in the ACT.

Research showed that a best practice water main failure prediction model is a physically based model that predicts time to failure for individual water mains based on the physical condition of the pipe and local environment influences. Physical models are time, cost and data intensive. Data and resource limitations meant that development of a physically based model was not feasible at this time. Instead efforts were concentrated on developing a statistical water main failure prediction model which is considered a simpler, cost effective alternative to a physical model.

The literature review identified pipe characteristics, soil embedment conditions and internal/external loading as important factors in the structural performance of buried pipes. Analysis showed that water main failures in the ACT are increasing over time and that seasonal influences are prominent. Most failures occur in winter and seem to also increase during warmer, dry periods. Frost loading, pipe and ground temperature differences and soil moisture were identified as likely causes.

As a result of this study, two basic multivariate failure prediction models were developed. Both of these models use similar techniques with time and rainfall being used as explanatory variables to predict total number of failures. The models differ in the time steps used in the model. Model 1 uses a time step of one month while Model 2 uses a time step of one year. Both models achieve comparable results.

Although relatively basic, the models both successfully met the criteria set out in the model development process. The models achieved accurate results considering the limitations of the study, the explanatory variables reflect the incidence of failures in the ACT and the data used in the models is readily available from existing failure records and the Bureau of Meteorology.

The models appear to compare quite well to other similar existing failure prediction models in terms of variables used, model output and prediction capabilities. Further testing and validation is required. There is scope to improve the accuracy of the model by identifying additional explanatory variables.

The statistical models produced by this study are useful tools that can assist in analysing and predicting system performance and some planning processes. However, the models do not have the capacity to predict when a pipe should be replaced instead of repaired. It may be worthwhile investigating the feasibility of developing a physically based model to perform this function.

7.2. Recommendations

While the results achieved in this study were positive, it must be noted that there were a number of issues that limited exactly what was able to be achieved. Also, the development of any model is an ongoing process.

Therefore, in order to overcome some of these limitations and further improve Actew's water main failure analysis and prediction capabilities the following recommendations are made.

- Compile historical failure records into a central water main failure database and add links to the GIS and asset management systems.
- Incorporate physical parameters into water main failure data collection processes.
- Conduct further testing, validation and improvement of the multivariate statistical models developed in this study.
- Conduct preliminary investigations into the development of a physically based water main failure prediction model.

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APPENDICES

APPENDIX A

PROJECT SPECIFICATION

PROJECT SPECIFICATION

University of Southern Queensland

FACULTY OF ENGINEERING AND SURVEYING

ENG 4111/4112 Research Project
PROJECT SPECIFICATION

FOR: GLEN ALANNE

TOPIC: DEVELOPING A MODEL TO PREDICT WATER MAIN BREAKS

SUPERVISORS: Vasantha Aravinthan (USQ)
Ray Hezkial (ActewAGL)

ENROLMENT: ENG 4111 – S1 2008
ENG 4112 – S2 2008

PROJECT AIM: To investigate common water main failure modes and existing water main failure prediction models and to use these findings to analyse ActewAGL performance data and develop a customised water main failure prediction model.

SPONSORSHIP: ActewAGL

PROGRAM: Issue A, 25 March 2008

1. Conduct a literature review on typical causes of water main failures.
2. Conduct a literature review of and critically evaluate existing water main failure models comparing methods used and limitations of the different methods.
3. Analyse the performance of ActewAGL's distribution/reticulation system in regard to water main breaks looking at relevant parameters identified in part 2 including pipe age, pipe material, pipe size, pressure zone and location.
4. Develop a customised ActewAGL water main prediction model based on available data looking at overcoming some of the limitations identified in part 2 and make recommendations regarding future data requirements to improve the model.
5. Compare the customised model with the other existing models.
6. Write and submit dissertation.

AGREED

_______________ (Student) _______________ _______________ (Supervisor)

26 / 3 / 08 ___/___/___ 26/03/2008

Examiner / Co-examiner _______________

APPENDIX B

RAW DATA

Model 1 Variables

	Failures	Month	Month^2	Month exp	Rain	Temp
Jul-78	263	0	0	247	583	98
Aug-78	265	1	1	248	575	96
Sep-78	263	2	4	249	647	87
Oct-78	252	3	9	249	670	87
Nov-78	236	4	16	250	716	84
Dec-78	228	5	25	250	771	84
Jan-79	236	6	36	251	640	84
Feb-79	244	7	49	252	637	84
Mar-79	242	8	64	252	645	84
Apr-79	233	9	81	253	658	86
May-79	228	10	100	254	595	93
Jun-79	230	11	121	254	559	104
Jul-79	243	12	144	255	514	111
Aug-79	237	13	169	255	544	111
Sep-79	243	14	196	256	436	114
Oct-79	250	15	225	257	446	110
Nov-79	256	16	256	257	450	111
Dec-79	283	17	289	258	392	111
Jan-80	260	18	324	259	463	111
Feb-80	254	19	361	259	520	111
Mar-80	271	20	400	260	399	111
Apr-80	297	21	441	261	345	112
May-80	312	22	484	261	377	101
Jun-80	327	23	529	262	404	94
Jul-80	301	24	576	263	434	87
Aug-80	305	25	625	263	413	87
Sep-80	296	26	676	264	398	89
Oct-80	294	27	729	265	409	89
Nov-80	292	28	784	265	409	88
Dec-80	267	29	841	266	477	88
Jan-81	284	30	900	267	432	88
Feb-81	286	31	961	267	515	88
Mar-81	282	32	1024	268	525	88
Apr-81	269	33	1089	269	537	90
May-81	267	34	1156	269	539	95
Jun-81	254	35	1225	270	619	89
Jul-81	267	36	1296	271	655	88
Aug-81	259	37	1369	271	691	76
Sep-81	259	38	1444	272	688	73
Oct-81	265	39	1521	273	670	73
Nov-81	271	40	1600	273	684	74
Dec-81	279	41	1681	274	651	74
Jan-82	255	42	1764	275	638	74
Feb-82	251	43	1849	275	516	74
Mar-82	234	44	1936	276	593	74
Apr-82	225	45	2025	277	588	67
May-82	246	46	2116	277	542	75
Jun-82	253	47	2209	278	446	86
Jul-82	253	48	2304	279	377	97
Aug-82	253	49	2401	280	330	113

Sep-82	256	50	2500	280	359	117
Oct-82	250	51	2601	281	340	123
Nov-82	248	52	2704	282	272	121
Dec-82	257	53	2809	282	262	121
Jan-83	270	54	2916	283	272	121
Feb-83	272	55	3025	284	287	121
Mar-83	293	56	3136	284	253	121
Apr-83	295	57	3249	285	293	122
May-83	270	58	3364	286	389	116
Jun-83	276	59	3481	287	403	106
Jul-83	280	60	3600	287	428	99
Aug-83	286	61	3721	288	468	90
Sep-83	290	62	3844	289	476	86
Oct-83	296	63	3969	289	582	78
Nov-83	296	64	4096	290	693	79
Dec-83	289	65	4225	291	757	79
Jan-84	274	66	4356	292	914	79
Feb-84	272	67	4489	292	940	79
Mar-84	289	68	4624	293	933	80
Apr-84	289	69	4761	294	982	80
May-84	291	70	4900	295	902	81
Jun-84	285	71	5041	295	882	93
Jul-84	283	72	5184	296	942	90
Aug-84	283	73	5329	297	951	86
Sep-84	270	74	5476	298	951	89
Oct-84	255	75	5625	298	877	96
Nov-84	255	76	5776	299	802	96
Dec-84	272	77	5929	300	740	97
Jan-85	317	78	6084	301	557	97
Feb-85	317	79	6241	301	507	97
Mar-85	298	80	6400	302	517	96
Apr-85	305	81	6561	303	445	97
May-85	337	82	6724	304	476	95
Jun-85	345	83	6889	304	501	91
Jul-85	360	84	7056	305	436	97
Aug-85	366	85	7225	306	497	100
Sep-85	375	86	7396	307	508	104
Oct-85	379	87	7569	307	528	100
Nov-85	364	88	7744	308	566	99
Dec-85	331	89	7921	309	568	98
Jan-86	314	90	8100	310	614	98
Feb-86	337	91	8281	310	606	98
Mar-86	377	92	8464	311	541	98
Apr-86	383	93	8649	312	574	96
May-86	340	94	8836	313	573	89
Jun-86	342	95	9025	314	547	90
Jul-86	331	96	9216	314	612	84
Aug-86	323	97	9409	315	545	86
Sep-86	318	98	9604	316	506	82
Oct-86	318	99	9801	317	516	85
Nov-86	322	100	10000	318	538	88
Dec-86	328	101	10201	318	530	88
Jan-87	343	102	10404	319	508	88

Feb-87	326	103	10609	320	592	88
Mar-87	277	104	10816	321	620	90
Apr-87	319	105	11025	322	575	96
May-87	321	106	11236	322	584	101
Jun-87	319	107	11449	323	618	98
Jul-87	317	108	11664	324	567	103
Aug-87	315	109	11881	325	559	98
Sep-87	322	110	12100	326	549	99
Oct-87	329	111	12321	326	534	98
Nov-87	340	112	12544	327	493	95
Dec-87	340	113	12769	328	588	96
Jan-88	316	114	12996	329	572	96
Feb-88	340	115	13225	330	534	96
Mar-88	370	116	13456	330	520	94
Apr-88	315	117	13689	331	609	88
May-88	322	118	13924	332	625	85
Jun-88	311	119	14161	333	640	78
Jul-88	321	120	14400	334	702	71
Aug-88	331	121	14641	335	707	77
Sep-88	329	122	14884	335	746	73
Oct-88	331	123	15129	336	717	73
Nov-88	328	124	15376	337	760	73
Dec-88	329	125	15625	338	765	72
Jan-89	333	126	15876	339	777	72
Feb-89	312	127	16129	340	735	72
Mar-89	283	128	16384	341	962	72
Apr-89	278	129	16641	341	1048	70
May-89	282	130	16900	342	1023	64
Jun-89	285	131	17161	343	992	66
Jul-89	284	132	17424	344	932	67
Aug-89	276	133	17689	345	907	65
Sep-89	285	134	17956	346	858	76
Oct-89	280	135	18225	347	859	81
Nov-89	283	136	18496	347	898	83
Dec-89	291	137	18769	348	825	83
Jan-90	319	138	19044	349	837	83
Feb-90	300	139	19321	350	913	83
Mar-90	322	140	19600	351	676	83
Apr-90	332	141	19881	352	626	85
May-90	318	142	20164	353	661	89
Jun-90	323	143	20449	354	654	92
Jul-90	321	144	20736	354	669	90
Aug-90	329	145	21025	355	689	85
Sep-90	316	146	21316	356	707	79
Oct-90	324	147	21609	357	735	75
Nov-90	339	148	21904	358	622	74
Dec-90	354	149	22201	359	617	74
Jan-91	310	150	22500	360	664	74
Feb-91	341	151	22801	361	603	74
Mar-91	371	152	23104	362	613	75
Apr-91	403	153	23409	363	491	79
May-91	463	154	23716	363	441	86
Jun-91	469	155	24025	364	520	77

Jul-91	472	156	24336	365	573	77
Aug-91	466	157	24649	366	599	79
Sep-91	476	158	24964	367	625	77
Oct-91	464	159	25281	368	588	74
Nov-91	452	160	25600	369	586	76
Dec-91	436	161	25921	370	598	76
Jan-92	441	162	26244	371	631	76
Feb-92	423	163	26569	372	685	76
Mar-92	362	164	26896	373	723	75
Apr-92	350	165	27225	374	740	73
May-92	349	166	27556	375	746	69
Jun-92	359	167	27889	375	672	80
Jul-92	396	168	28224	376	581	85
Aug-92	413	169	28561	377	586	92
Sep-92	402	170	28900	378	595	90
Oct-92	415	171	29241	379	652	88
Nov-92	410	172	29584	380	742	88
Dec-92	402	173	29929	381	770	88
Jan-93	405	174	30276	382	788	88
Feb-93	425	175	30625	383	748	88
Mar-93	425	176	30976	384	794	88
Apr-93	424	177	31329	385	784	85
May-93	394	178	31684	386	766	95
Jun-93	396	179	32041	387	767	97
Jul-93	364	180	32400	388	872	92
Aug-93	343	181	32761	389	818	89
Sep-93	345	182	33124	390	832	89
Oct-93	343	183	33489	391	809	96
Nov-93	347	184	33856	392	765	95
Dec-93	360	185	34225	393	703	95
Jan-94	386	186	34596	394	579	95
Feb-94	384	187	34969	395	613	95
Mar-94	407	188	35344	396	531	95
Apr-94	388	189	35721	397	579	95
May-94	411	190	36100	398	564	91
Jun-94	430	191	36481	399	574	86
Jul-94	449	192	36864	400	462	95
Aug-94	487	193	37249	401	442	100
Sep-94	504	194	37636	402	365	112
Oct-94	504	195	38025	403	356	111
Nov-94	521	196	38416	404	335	109
Dec-94	504	197	38809	405	380	109
Jan-95	476	198	39204	406	589	109
Feb-95	455	199	39601	407	526	109
Mar-95	474	200	40000	408	513	111
Apr-95	533	201	40401	409	453	121
May-95	495	202	40804	410	585	111
Jun-95	476	203	41209	411	589	113
Jul-95	465	204	41616	412	633	106
Aug-95	437	205	42025	413	636	101
Sep-95	420	206	42436	414	676	87
Oct-95	418	207	42849	415	742	84
Nov-95	399	208	43264	416	834	85

Dec-95	401	209	43681	417	827	85
Jan-96	399	210	44100	418	694	85
Feb-96	416	211	44521	419	728	85
Mar-96	380	212	44944	420	745	84
Apr-96	365	213	45369	421	752	78
May-96	367	214	45796	422	673	87
Jun-96	377	215	46225	423	670	85
Jul-96	365	216	46656	424	690	85
Aug-96	359	217	47089	425	730	83
Sep-96	366	218	47524	426	776	81
Oct-96	362	219	47961	428	730	79
Nov-96	354	220	48400	429	671	80
Dec-96	375	221	48841	430	671	80
Jan-97	394	222	49284	431	637	80
Feb-97	394	223	49729	432	628	80
Mar-97	420	224	50176	433	638	80
Apr-97	420	225	50625	434	620	84
May-97	471	226	51076	435	592	81
Jun-97	514	227	51529	436	675	86
Jul-97	536	228	51984	437	614	96
Aug-97	556	229	52441	438	595	103
Sep-97	564	230	52900	439	590	102
Oct-97	562	231	53361	441	537	104
Nov-97	567	232	53824	442	478	103
Dec-97	581	233	54289	443	427	103
Jan-98	593	234	54756	444	399	103
Feb-98	596	235	55225	445	408	103
Mar-98	623	236	55696	446	381	102
Apr-98	598	237	56169	447	432	94
May-98	562	238	56644	448	439	90
Jun-98	523	239	57121	449	439	82
Jul-98	510	240	57600	451	497	74
Aug-98	494	241	58081	452	590	60
Sep-98	482	242	58564	453	563	59
Oct-98	485	243	59049	454	611	59
Nov-98	484	244	59536	455	672	60
Dec-98	451	245	60025	456	676	60
Jan-99	428	246	60516	457	751	60
Feb-99	437	247	61009	459	723	60
Mar-99	408	248	61504	460	790	60
Apr-99	395	249	62001	461	792	64
May-99	392	250	62500	462	777	72
Jun-99	391	251	63001	463	695	82
Jul-99	414	252	63504	464	641	84
Aug-99	425	253	64009	465	567	94
Sep-99	428	254	64516	467	580	98
Oct-99	436	255	65025	468	624	95
Nov-99	443	256	65536	469	585	96
Dec-99	440	257	66049	470	709	96
Jan-00	438	258	66564	471	647	97
Feb-00	426	259	67081	473	651	97
Mar-00	419	260	67600	474	624	97
Apr-00	420	261	68121	475	631	97

May-00	426	262	68644	476	666	95
Jun-00	434	263	69169	477	657	93
Jul-00	417	264	69696	478	671	93
Aug-00	413	265	70225	480	676	92
Sep-00	412	266	70756	481	692	93
Oct-00	413	267	71289	482	642	100
Nov-00	402	268	71824	483	722	98
Dec-00	405	269	72361	484	601	100
Jan-01	410	270	72900	486	605	99
Feb-01	396	271	73441	487	689	99
Mar-01	385	272	73984	488	694	100
Apr-01	414	273	74529	489	643	102
May-01	459	274	75076	491	588	109
Jun-01	470	275	75625	492	585	109
Jul-01	472	276	76176	493	593	110
Aug-01	478	277	76729	494	604	109
Sep-01	478	278	77284	496	580	108
Oct-01	470	279	77841	497	569	109
Nov-01	486	280	78400	498	491	111
Dec-01	499	281	78961	499	490	110
Jan-02	504	282	79524	500	476	110
Feb-02	514	283	80089	502	589	110
Mar-02	505	284	80656	503	581	109
Apr-02	479	285	81225	504	592	104
May-02	462	286	81796	506	616	100
Jun-02	459	287	82369	507	632	96
Jul-02	490	288	82944	508	610	98
Aug-02	477	289	83521	509	572	105
Sep-02	483	290	84100	511	568	110
Oct-02	487	291	84681	512	534	113
Nov-02	503	292	85264	513	501	114
Dec-02	525	293	85849	514	504	114
Jan-03	548	294	86436	516	489	114
Feb-03	564	295	87025	517	334	114
Mar-03	562	296	87616	518	351	116
Apr-03	587	297	88209	520	345	118
May-03	605	298	88804	521	333	116
Jun-03	632	299	89401	522	339	112
Jul-03	615	300	90000	524	360	107
Aug-03	653	301	90601	525	403	103
Sep-03	656	302	91204	526	390	104
Oct-03	654	303	91809	527	438	103
Nov-03	637	304	92416	529	500	101
Dec-03	603	305	93025	530	569	100
Jan-04	567	306	93636	531	607	100
Feb-04	573	307	94249	533	573	100
Mar-04	616	308	94864	534	519	98
Apr-04	640	309	95481	535	506	97
May-04	679	310	96100	537	498	102
Jun-04	680	311	96721	538	463	103
Jul-04	724	312	97344	539	437	105
Aug-04	717	313	97969	541	403	101
Sep-04	733	314	98596	542	406	99

Oct-04	739	315	99225	544	401	90
Nov-04	743	316	99856	545	414	88
Dec-04	740	317	100489	546	399	88
Jan-05	739	318	101124	548	407	88
Feb-05	729	319	101761	549	459	88
Mar-05	695	320	102400	550	495	89
Apr-05	630	321	103041	552	499	88
May-05	583	322	103684	553	494	82
Jun-05	577	323	104329	555	555	81
Jul-05	561	324	104976	556	630	77
Aug-05	539	325	105625	557	651	82
Sep-05	524	326	106276	559	702	80
Oct-05	518	327	106929	560	726	78
Nov-05	501	328	107584	561	712	78
Dec-05	510	329	108241	563	659	78
Jan-06	513	330	108900	564	687	78
Feb-06	498	331	109561	566	640	78
Mar-06	508	332	110224	567	633	77
Apr-06	565	333	110889	569	642	86
May-06	589	334	111556	570	652	89
Jun-06	579	335	112225	571	654	97
Jul-06	542	336	112896	573	604	96
Aug-06	544	337	113569	574	562	100
Sep-06	540	338	114244	576	482	103
Oct-06	540	339	114921	577	407	112
Nov-06	545	340	115600	579	376	115
Dec-06	549	341	116281	580	373	115
Jan-07	569	342	116964	581	297	115
Feb-07	572	343	117649	583	364	115
Mar-07	571	344	118336	584	366	115
Apr-07	548	345	119025	586	378	104
May-07	488	346	119716	587	409	95
Jun-07	512	347	120409	589	427	89
Jul-07	532	348	121104	590	410	94
Aug-07	524	349	121801	592	410	81
Sep-07	516	350	122500	593	407	83
Oct-07	510	351	123201	595	425	77
Nov-07	499	352	123904	596	479	74
Dec-07	491	353	124609	598	563	74
Jan-08	467	354	125316	599	600	74
Feb-08	454	355	126025	601	573	74
Mar-08	448	356	126736	602	569	74
Apr-08	469	357	127449	604	558	77
May-08	547	358	128164	605	530	86
Jun-08	499	359	128881	607	458	82

Model 2 Variables

	Failures	Month	Month^2	Month exp	Rain	Temp
Oct-78	252	0	0	242	670	87
Oct-79	250	1	1	249	446	110
Oct-80	294	2	4	257	409	89
Oct-81	265	3	9	265	670	73
Oct-82	250	4	16	273	340	123
Oct-83	296	5	25	281	582	78
Oct-84	255	6	36	290	877	96
Oct-85	379	7	49	299	528	100
Oct-86	318	8	64	308	516	85
Oct-87	329	9	81	318	534	98
Oct-88	331	10	100	328	717	73
Oct-89	280	11	121	338	859	81
Oct-90	324	12	144	348	735	75
Oct-91	464	13	169	359	588	74
Oct-92	415	14	196	370	652	88
Oct-93	343	15	225	381	809	96
Oct-94	504	16	256	393	356	111
Oct-95	418	17	289	405	742	84
Oct-96	362	18	324	418	730	79
Oct-97	562	19	361	431	537	104
Oct-98	485	20	400	444	611	59
Oct-99	436	21	441	458	624	95
Oct-00	413	22	484	472	642	100
Oct-01	470	23	529	486	569	109
Oct-02	487	24	576	501	534	113
Oct-03	654	25	625	517	438	103
Oct-04	739	26	676	533	401	90
Oct-05	518	27	729	549	726	78
Oct-06	540	28	784	566	407	112
Oct-07	510	29	841	584	425	77

Monthly Rainfall

CANBERRA AIRPORT

Station Number: 070014 · State: NSW · Opened: 1939 · Status: Open · Latitude: 35.30°S · Longitude: 149.20°E · Elevation: 578 m

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1939			94.7	75.0	21.5	57.7	33.3	110.1	16.1	77.0	49.7	21.6	
1940	35.6	3.8	2.3	154.1	11.5	11.6	6.5	21.6	56.6	6.4	13.2	49.5	372.7
1941	163.9	74.8	25.8	19.2	40.2	36.9	10.6	22.4	70.3	29.8	21.4	26.6	541.9
1942	7.4	95.5	20.9	2.1	117.2	79.6	43.6	48.8	57.7	42.6	109.6	15.4	640.4
1943	68.5	1.6	11.4	71.5	61.7	13.2	25.0	46.4	53.7	83.2	99.9	45.2	581.3
1944	4.2	16.3	29.4	19.6	48.2	6.6	29.4	7.2	16.0	36.5	55.6	35.6	304.6
1945	117.3	83.6	15.3	102.6	21.1	36.4	31.0	54.2	11.5	47.6	59.9	23.4	603.9
1946	97.7	84.7	37.0	32.5	19.8	27.6	44.5	15.8	6.0	44.9	86.0	26.6	523.1
1947	1.1	83.7	35.7	27.7	23.6	25.9	37.6	49.7	62.8	26.5	79.7	215.2	669.2
1948	117.0	144.7	23.0	55.2	142.9	53.8	15.0	17.5	49.6	61.0	29.3	92.5	801.5
1949	30.0	81.1	78.3	26.4	95.4	27.7	43.8	9.8	70.2	101.5	66.4	16.3	646.9
1950	79.7	77.7	312.2	90.7	65.0	18.8	75.4	38.0	36.3	137.8	113.6	17.3	1062.5
1951	36.6	31.2	2.6	16.4	30.1	79.1	42.8	77.3	49.3	59.8	26.2	8.6	460.0
1952	21.8	9.2	143.9	120.8	65.7	108.3	39.3	66.0	71.6	126.7	60.8	131.3	965.4
1953	46.5	16.8	23.2	24.0	149.6	20.3	14.2	31.0	51.8	43.1	38.7	35.0	494.2
1954	87.2	56.8	1.3	36.4	7.2	38.9	15.8	26.3	16.7	56.5	79.6	35.0	457.7
1955	22.9	87.0	21.0	23.9	103.9	53.1	28.6	106.0	25.7	127.7	72.5	63.2	735.5
1956	79.5	55.3	196.4	79.7	69.4	126.0	67.2	45.6	43.3	98.9	20.3	6.7	888.3
1957	18.4	27.9	31.0	19.0	8.6	31.8	61.8	42.0	8.1	15.0	23.0	54.9	341.5
1958	85.1	25.9	31.1	53.6	34.1	62.2	54.0	59.7	50.5	60.2	33.8	62.9	613.1
1959	66.3	106.3	116.5	101.5	14.4	103.3	34.7	11.6	34.3	147.7	122.0	33.9	892.5
1960	113.2	15.0	43.2	19.9	75.1	8.3	103.6	25.5	96.0	85.4	68.1	160.3	813.6
1961	43.0	67.7	128.4	51.0	1.6	25.2	71.4	34.8	28.5	36.2	134.9	151.5	774.2
1962	108.0	47.7	24.0	19.3	53.3	8.8	32.8	55.1	113.7	45.3	35.6	110.4	654.0
1963	88.3	43.8	56.4	65.0	77.0	34.3	37.9	34.5	52.8	24.1	41.0	64.0	619.1
1964	25.5	21.6	24.6	123.6	36.1	23.6	85.7	41.7	71.6	122.4	21.7	45.0	643.1
1965	1.3	1.5	1.7	10.4	11.7	20.4	15.8	49.5	73.4	137.0	32.3	45.3	400.3
1966	49.3	69.6	73.5	3.4	37.9	44.1	28.9	48.8	65.7	89.8	105.2	75.9	692.1
1967	56.4	14.8	10.2	8.9	17.7	16.4	12.4	89.7	31.5	49.3	44.7	0.0	352.0
1968	38.4	0.0	32.1	38.7	134.2	22.5	22.4	58.3	12.4	50.5	23.7	82.0	515.2
1969	17.0	106.6	50.2	82.4	41.9	58.7	44.5	51.0	40.6	139.5	94.3	32.4	759.1
1970	59.5	94.8	60.0	51.5	34.2	29.4	4.2	54.5	115.7	31.9	111.6	75.1	722.4
1971	115.0	109.6	24.3	19.3	23.1	4.8	13.5	47.6	43.7	37.4	82.6	95.1	616.0
1972	60.5	45.9	23.9	22.0	39.1	9.0	6.8	68.0	12.6	53.0	52.0	3.3	396.1
1973	46.7	135.0	46.6	8.2	52.2	29.6	70.5	64.1	38.2	104.2	117.3	42.4	755.0
1974	105.8	87.6	43.8	164.4	49.8	21.8	43.2	156.2	64.2	145.6	92.0	2.6	977.0
1975	72.0	109.2	47.2	50.2	15.2	83.4	72.2	37.8	102.2	111.0	39.0	31.6	771.0
1976	79.0	81.0	29.8	41.6	0.8	12.0	30.0	23.4	65.0	161.0	49.6	19.6	592.8
1977	28.4	148.2	62.8	51.0	73.4	28.2	9.4	21.0	79.2	2.4	4.4	4.6	513.0
1978	136.6	4.0	122.0	42.6	74.6	40.8	51.0	13.2	150.6	25.2	51.2	59.2	771.0
1979	6.0	0.8	129.8	55.4	12.2	4.0	6.0	43.4	42.4	36.0	55.2	1.0	392.2
1980	77.0	57.2	9.6	1.0	44.2	31.0	36.2	22.2	27.4	47.0	55.4	68.6	476.8
1981	32.0	140.2	19.8	12.6	46.8	110.4	72.8	57.8	24.2	29.4	69.0	36.4	651.4
1982	18.2	18.4	97.4	7.6	0.0	14.8	3.8	10.8	53.2	10.8	0.2	26.4	261.6

Quality control: 12.3 Done & acceptable, 12.3 Not completed or unknown

Monthly Rainfall

CANBERRA AIRPORT

Station Number: 070014 - State: NSW - Opened: 1939 - Status: Open - Latitude: 35.30°S - Longitude: 149.20°E - Elevation: 578 m

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1983	28.6	33.2	63.6	47.2	96.4	28.8	29.2	50.2	61.4	116.6	111.6	90.2	757.0
1984	185.4	59.2	56.4	97.0	16.4	8.4	89.2	58.8	62.0	42.6	36.2	28.0	739.6
1985	2.8	8.8	67.2	24.6	47.6	33.2	24.0	120.2	72.6	63.2	73.8	29.8	567.8
1986	49.2	0.4	2.2	57.4	47.4	6.6	88.8	53.8	33.6	73.0	96.2	21.0	529.6
1987	27.2	84.8	30.4	12.4	56.6	40.4	37.8	45.4	24.0	57.8	55.0	116.0	587.8
1988	11.6	46.6	16.8	100.8	72.4	56.0	99.8	49.8	63.2	29.2	97.4	121.4	765.0
1989	23.2	4.8	243.6	187.2	47.0	25.0	40.6	24.2	14.0	30.4	136.2	49.2	825.4
1990	35.0	80.8	6.2	137.6	82.2	18.0	55.4	44.4	32.0	58.4	23.2	44.0	617.2
1991	82.2	19.2	16.0	16.2	32.2	97.0	108.0	70.6	57.6	21.8	21.4	56.0	598.2
1992	115.0	73.0	54.4	33.0	38.0	23.6	16.8	75.0	67.4	78.8	111.0	84.8	770.8
1993	133.0	32.4	100.8	22.4	20.0	25.4	121.0	12.4	80.6	54.4	66.6	23.2	692.2
1994	9.2	66.4	21.4	70.4	5.8	35.0	9.2	2.0	3.0	46.8	46.4	67.8	383.4
1995	218.4	3.6	4.4	10.8	137.4	38.8	53.4	5.2	42.8	87.0	138.2	61.0	801.0
1996	85.0	38.4	20.6	18.2	59.8	35.8	73.0	45.4	88.6	67.6	79.2	61.0	672.6
1997	48.6	29.2	29.6	0.8	29.4	110.2	11.0	24.2	84.0	15.0	20.0	9.8	411.8
1998	22.8	38.4	3.6	51.4	37.8	117.4	69.8	118.6	57.0	59.0	79.6	13.8	669.2
1999	97.4	10.0	70.8	53.8	23.0	35.8	18.2	45.6	70.0	106.2	41.4	139.6	711.8
2000	35.8	14.6	43.4	61.8	58.0	26.6	31.0	64.6	85.6	56.8	121.2	27.0	626.4
2001	40.4	98.0	48.6	10.6	2.6	31.8	38.8	60.8	62.2	45.6	45.4	15.2	500.0
2002	26.4	211.0	40.8	21.2	27.0	40.8	16.8	22.8	58.4	11.6	10.4	18.2	505.4
2003	11.4	55.2	58.4	15.4	14.6	46.6	36.4	66.2	44.8	59.6	73.2	87.4	569.2
2004	49.0	21.4	4.4	2.4	6.6	11.6	10.8	67.8	48.0	55.0	85.8	72.4	435.2
2005	57.2	73.6	40.2	6.8	0.8	73.0	86.4	45.8	100.6	61.0	83.4	19.8	648.6
2006	79.0	23.8	30.8	14.8	9.4	74.4	36.4	11.6	18.4	4.0	41.8	16.8	361.2
2007	9.6	95.2	36.6	27.8	41.6	92.8	18.8	11.6	14.6	23.4	95.4	101.0	568.4
2008	*43.8*	*64.6*	*30.0*	*17.4*	*12.8*	*21.8*	*44.0*	*17.6*	*40.8*				

Monthly Rainfall

CANBERRA AIRPORT

Station Number: 070014 - State: NSW - Opened: 1939 - Status: Open - Latitude: 35.30°S - Longitude: 149.20°E - Elevation: 578 m

Statistics for this station calculated over all years of data

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	59.3	56.1	50.8	46.0	44.7	40.8	41.3	46.2	52.1	62.7	64.2	52.5	616.8
Lowest	1.1	0.0	1.3	0.8	0.0	4.0	3.8	2.0	3.0	2.4	0.2	0.0	261.6
5th percentile	4.9	1.5	2.4	2.8	2.0	7.4	6.6	10.2	11.9	11.1	15.9	3.8	355.2
10th percentile	9.5	4.0	4.4	8.1	7.1	9.0	10.5	11.6	14.5	20.4	21.4	9.6	389.6
Median	48.6	55.2	31.6	30.1	38.0	31.4	36.4	45.6	52.3	55.0	59.9	42.4	618.2
90th percentile	115.4	107.1	117.1	101.6	95.5	93.2	85.8	75.2	85.9	126.9	112.0	111.5	805.1
95th percentile	135.2	138.1	137.6	131.3	126.6	109.3	95.0	108.3	101.5	138.8	121.7	136.3	891.0
Highest	218.4	211.0	312.2	187.2	149.6	126.0	121.0	156.2	150.6	161.0	138.2	215.2	1062.5

Statistics calculated over the period 1961-1990

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	54.2	57.5	53.5	53.1	44.8	29.7	41.2	51.0	55.7	65.3	64.7	52.4	623.2
Lowest	1.3	0.0	1.7	1.0	0.0	4.0	3.8	10.8	12.4	2.4	0.2	0.0	261.6
5th Percentile	4.2	0.6	4.0	5.3	1.2	5.6	5.0	16.7	13.2	16.8	12.2	1.7	370.1
10th percentile	11.0	1.4	9.3	8.1	10.7	8.2	6.7	22.1	23.0	25.1	23.0	3.2	395.7
Median	44.8	52.5	45.2	44.9	45.5	25.1	37.0	49.2	53.0	49.9	55.1	44.5	631.1
90th percentile	108.7	112.1	122.6	125.0	77.5	56.3	86.0	70.2	103.3	137.2	112.2	111.0	771.3
95th percentile	126.9	137.9	129.2	152.3	90.0	72.3	89.0	106.5	114.8	142.9	127.0	119.0	802.4
Highest	185.4	148.2	243.6	187.2	134.2	110.4	99.8	156.2	150.6	161.0	136.2	151.5	977.0

1) Calculation of statistics

Summary statistics, other than the Highest and Lowest values, are only calculated if there are at least 20 years of data available.

2) Gaps and missing data

Gaps may be caused by a damaged instrument, a temporary change to the site operation, or due to the absence or illness of an observer.

3) Further information

http://www.bom.gov.au/climate/cdo/about/about-rain-data.shtml.

Product code: IDCJAC0001 reference: 00075760

Climate Data Reproduced from Bureau of Meteorology Website

Statistics	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Number of days ground min. temp. ≤ -1 °C for year 1977	0	0	0	9	8	19	26	24	16	7	4	0	113.0
Number of days ground min. temp. ≤ -1 °C for year 1978	0	0	0	4	11	14	18	22	7	7	1	0	84.0
Number of days ground min. temp. ≤ -1 °C for year 1979	0	0	0	6	18	25	26	22	10	3	2	0	112.0
Number of days ground min. temp. ≤ -1 °C for year 1980	0	0	0	7	7	18	18	22	12	3	1	0	88.0
Number of days ground min. temp. ≤ -1 °C for year 1981	0	0	0	9	12	12	17	10	9	2	2	0	73.0
Number of days ground min. temp. ≤ -1 °C for year 1982	0	0	0	2	20	23	28	26	13	9	0	0	121.0
Number of days ground min. temp. ≤ -1 °C for year 1983	0	0	0	3	4	13	21	17	9	1	1	0	69.0
Number of days ground min. temp. ≤ -1 °C for year 1984	0	0	1	3	15	25	18	13	12	8	1	1	97.0
Number of days ground min. temp. ≤ -1 °C for year 1985	0	0	0	4	13	21	24	16	16	4	0	0	98.0
Number of days ground min. temp. ≤ -1 °C for year 1986	0	0	0	2	6	22	18	18	12	7	3	0	88.0
Number of days ground min. temp. ≤ -1 °C for year 1987	0	0	2	8	11	19	23	13	13	6	0	1	96.0
Number of days ground min. temp. ≤ -1 °C for year 1988	0	0	0	2	8	12	16	19	9	6	0	0	72.0
Number of days ground min. temp. ≤ -1 °C for year 1989	0	0	0	0	2	14	17	17	20	11	2	0	83.0
Number of days ground min. temp. ≤ -1 °C for year 1990	0	0	0	2	6	17	15	12	14	7	1	0	74.0
Number of days ground min. temp. ≤ -1 °C for year 1991	0	0	1	6	13	8	15	14	12	4	3	0	76.0
Number of days ground min. temp. ≤ -1 °C for year 1992	0	0	0	4	9	19	20	21	10	2	3	0	88.0

Statistics	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Number of days ground min. temp. ≤ -1 °C for year 1993	0	0	0	1	19	21	15	18	10	9	2	0	95.0
Number of days ground min. temp. ≤ -1 °C for year 1994	0	0	0	1	15	16	24	23	22	8	0	0	109.0
Number of days ground min. temp. ≤ -1 °C for year 1995	0	0	2	11	5	18	17	18	8	5	1	0	85.0
Number of days ground min. temp. ≤ -1 °C for year 1996	0	0	1	5	14	16	17	16	6	3	2	0	80.0
Number of days ground min. temp. ≤ -1 °C for year 1997	0	0	1	9	11	21	27	23	5	5	1	0	103.0
Number of days ground min. temp. ≤ -1 °C for year 1998	0	0	0	1	7	13	19	9	4	5	2	0	60.0
Number of days ground min. temp. ≤ -1 °C for year 1999	0	0	0	5	15	23	21	19	8	2	3	0	96.0
Number of days ground min. temp. ≤ -1 °C for year 2000	1	0	0	5	13	21	21	18	9	9	1	2	100.0
Number of days ground min. temp. ≤ -1 °C for year 2001	0	0	1	7	20	21	22	17	8	10	3	1	110.0
Number of days ground min. temp. ≤ -1 °C for year 2002	0	0	0	2	16	17	24	24	13	13	4	1	114.0
Number of days ground min. temp. ≤ -1 °C for year 2003	0	0	2	4	14	13	19	20	14	12	2	0	100.0
Number of days ground min. temp. ≤ -1 °C for year 2004	0	0	0	3	19	14	21	16	12	3	0	0	88.0
Number of days ground min. temp. ≤ -1 °C for year 2005	0	0	1	2	13	13	17	21	10	1	0	0	78.0
Number of days ground min. temp. ≤ -1 °C for year 2006	0	0	0	11	16	21	16	25	13	10	3	0	115.0
Number of days ground min. temp. ≤ -1 °C for year 2007	0	0	0	0	7	15	21	12	15	4	0	0	74.0
Number of days ground min. temp. ≤ -1 °C for year 2008	0	0	0	3	16	11	23	22	12				

APPENDIX C

PROJECT DATA ANALYSIS

PROJECT MODEL 1

Regression Output for Failures versus Time (linear)

SUMMARY OUTPUT

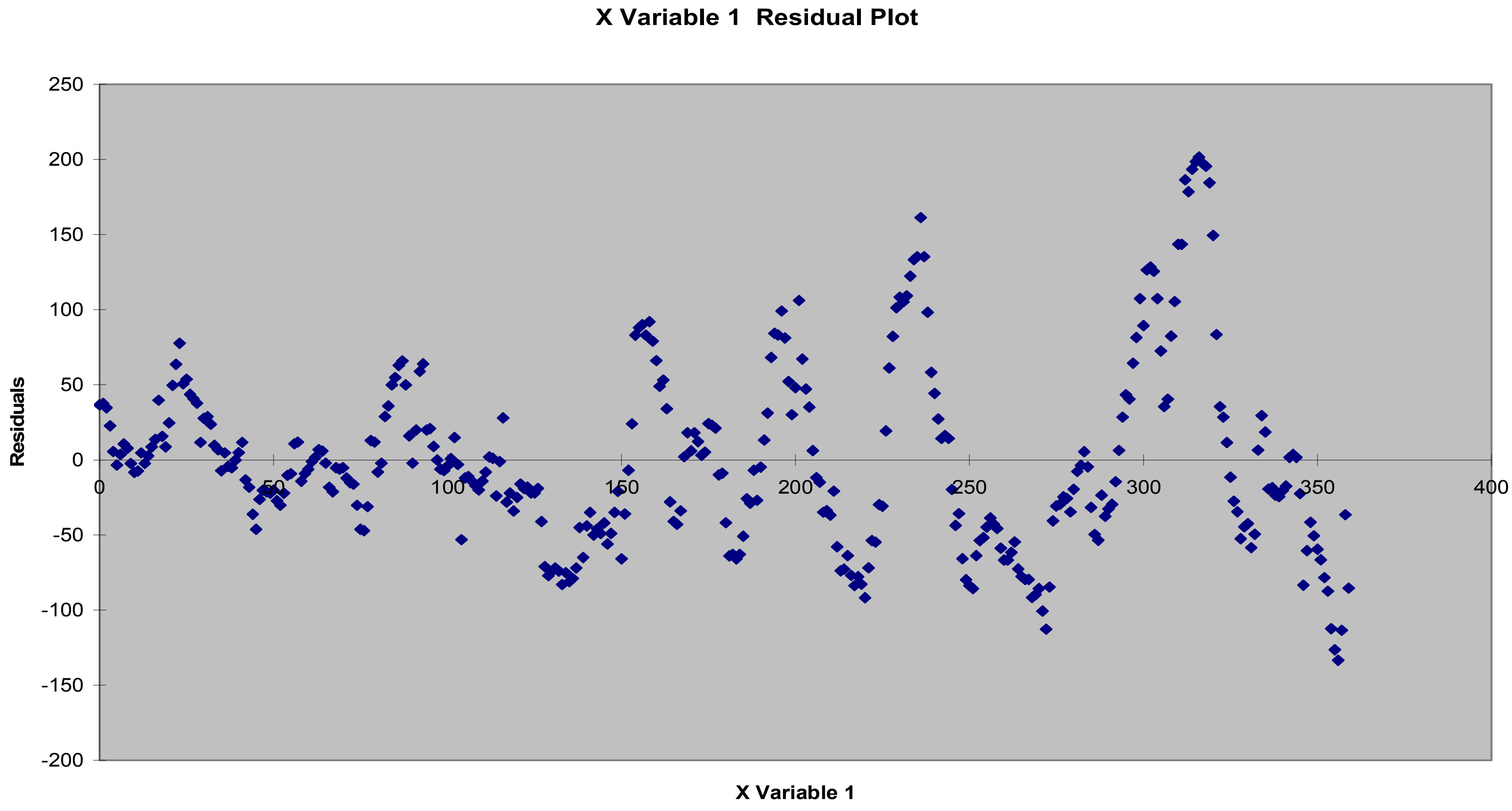
Regression Statistics	
Multiple R	0.862047711
R Square	0.743126256
Adjusted R Square	0.742408731
Standard Error	61.10799069
Observations	360

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	3867425.213	3867425.213	1035.681	1.068E-107
Residual	358	1336838.776	3734.186526		
Total	359	5204263.989			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	226.369329	6.427951562	35.21640243	2.4E-118	213.7280395	239.010619	213.728039	239.0106186
X Variable 1	0.997354403	0.030991069	32.18199465	1.1E-107	0.936406982	1.05830182	0.93640698	1.058301825

Residual Plot for Failures versus Time (linear)



Regression Output for Failures versus Time (exp)

SUMMARY OUTPUT

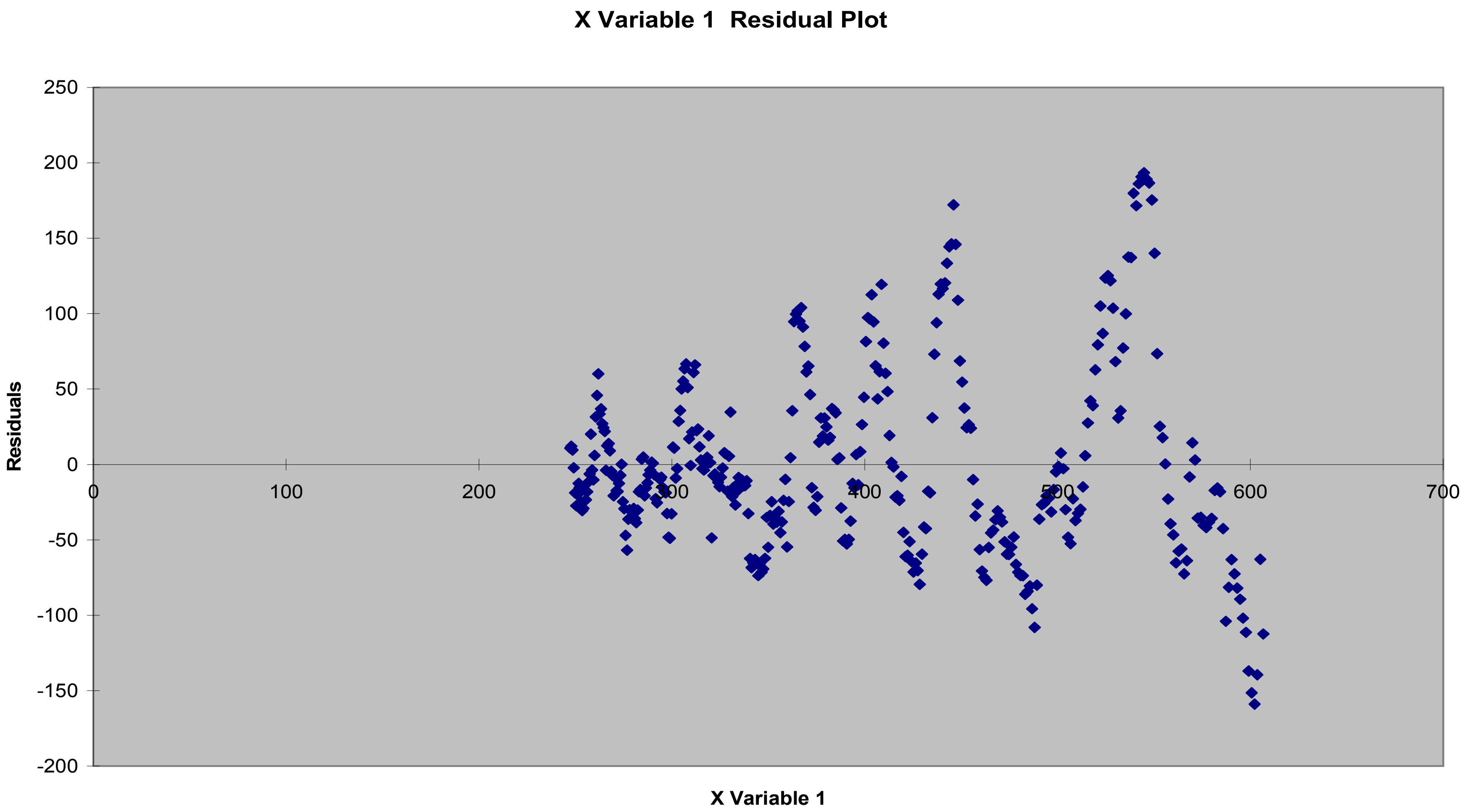
Regression Statistics	
Multiple R	0.858989
R Square	0.737862
Adjusted R Square	0.737129
Standard Error	61.73102
Observations	360

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	3840026	3840026	1007.691	4E-106
Residual	358	1364238	3810.719		
Total	359	5204264			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	5.209198	13.01965	0.400103	0.689319	-20.3954	30.81381	-20.3954	30.81381
X Variable 1	0.999051	0.031472	31.74414	4E-106	0.937158	1.060944	0.937158	1.060944

Residual Plot for Failures versus Time (exp)



Regression Output for Failures versus Rainfall

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.340969
R Square	0.11626
Adjusted R Square	0.113791
Standard Error	113.3445
Observations	360

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	605045.9	605045.9	47.09636	2.99E-11
Residual	358	4599218	12846.98		
Total	359	5204264			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	567.6119	24.38081	23.2811	1.17E-73	519.6643	615.5595	519.6643	615.5595
X Variable 1	-0.27447	0.039995	-6.86268	2.99E-11	-0.35313	-0.19582	-0.35313	-0.19582

Regression Output for Failures versus Time (exp) and Rainfall

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.885604548
R Square	0.784295416
Adjusted R Square	0.783086987
Standard Error	56.075769
Observations	360

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	4081680.392	2040840.196	649.0207	1.2414E-119
Residual	357	1122583.597	3144.491869		
Total	359	5204263.989			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	123.9970425	17.98575791	6.894179446	2.47E-11	88.62569104	159.368394	88.62569104	159.3683939
X Variable 1	0.961318398	0.028910991	33.25096718	2.3E-111	0.904461144	1.01817565	0.904461144	1.018175653
X Variable 2	-0.175416388	0.020010064	-8.766408221	7.62E-17	-0.214768802	-0.136064	-0.214768802	-0.136063973

Regression Output for Failures versus Time (exp) and Temperature

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.868838
R Square	0.754879
Adjusted R Square	0.753506
Standard Error	59.77725
Observations	360

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	3928589	1964294	549.7113	1E-109
Residual	357	1275675	3573.32		
Total	359	5204264			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-94.1744	23.61089	-3.9886	8.07E-05	-140.608	-47.7405	-140.608	-47.7405
X Variable 1	0.987548	0.030563	32.31149	5E-108	0.927441	1.047655	0.927441	1.047655
X Variable 2	1.138765	0.228742	4.978383	1E-06	0.688914	1.588616	0.688914	1.588616

Regression Output for Failures versus Time (exp), Rainfall and Temperature

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.885622
R Square	0.784326
Adjusted R Square	0.782509
Standard Error	56.15044
Observations	360

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	4081842	1360614	431.5475	3.5E-118
Residual	356	1122422	3152.872		
Total	359	5204264			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	116.5608	37.49016	3.109102	0.002028	42.83073	190.2908	42.83073	190.2908
X Variable 1	0.961416	0.028953	33.20645	4.6E-111	0.904476	1.018355	0.904476	1.018355
X Variable 2	-0.17215	0.024692	-6.9719	1.53E-11	-0.22071	-0.12359	-0.22071	-0.12359
X Variable 3	0.059884	0.264789	0.226157	0.821209	-0.46086	0.58063	-0.46086	0.58063

PROJECT MODEL 2

Regression Output for Failures versus Time (linear)

SUMMARY OUTPUT

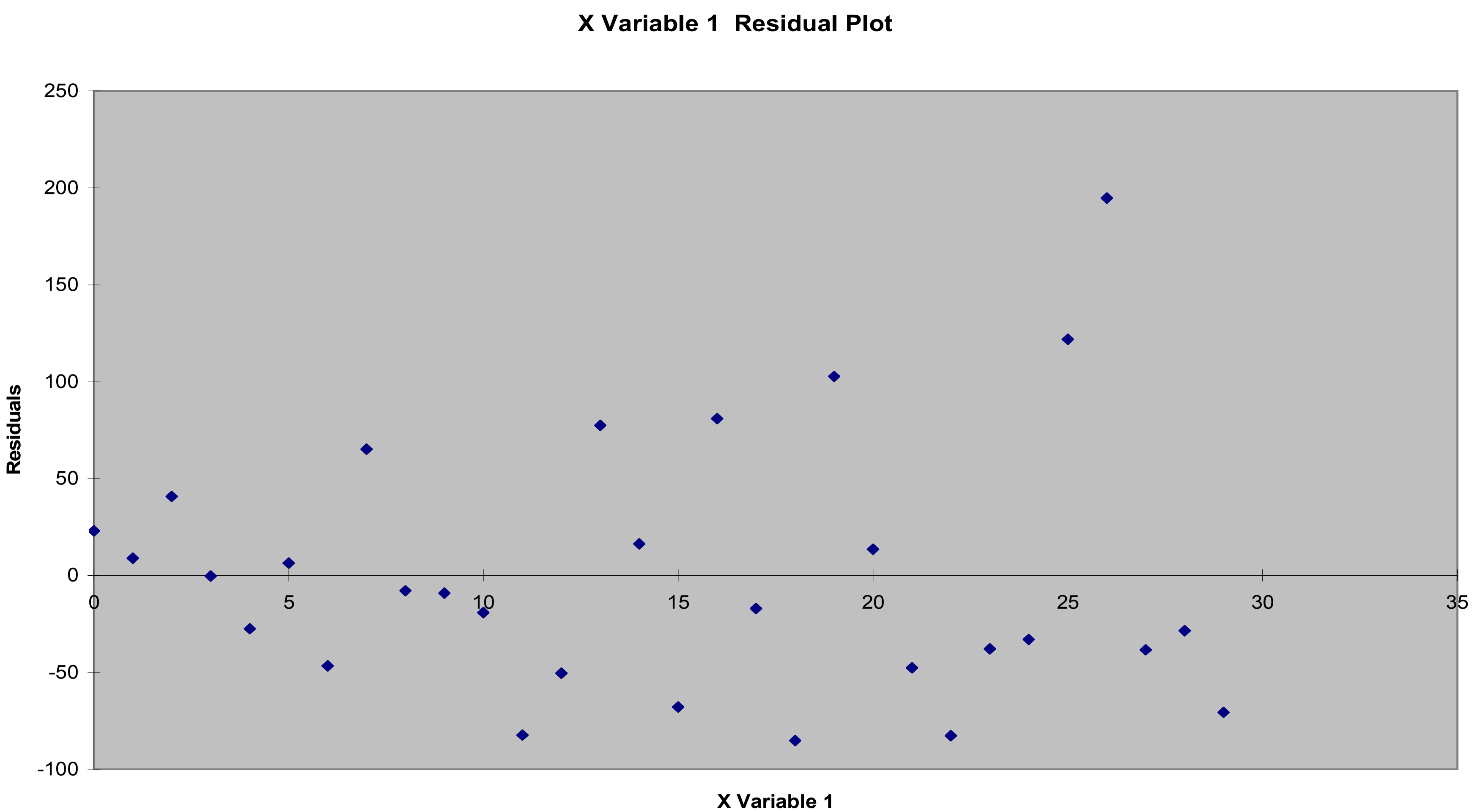
Regression Statistics	
Multiple R	0.850211
R Square	0.722858
Adjusted R Square	0.71296
Standard Error	67.27684
Observations	30

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	330552.5	330552.5	73.03135	2.74E-09
Residual	28	126732.8	4526.173		
Total	29	457285.4			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	228.9183	23.96432	9.552463	2.62E-10	179.8296	278.007	179.8296	278.007
X Variable 1	12.12747	1.419109	8.545838	2.74E-09	9.220562	15.03439	9.220562	15.03439

Residual Plot for Failures versus Time (linear)



Regression Output for Failures versus Time (exp)

SUMMARY OUTPUT

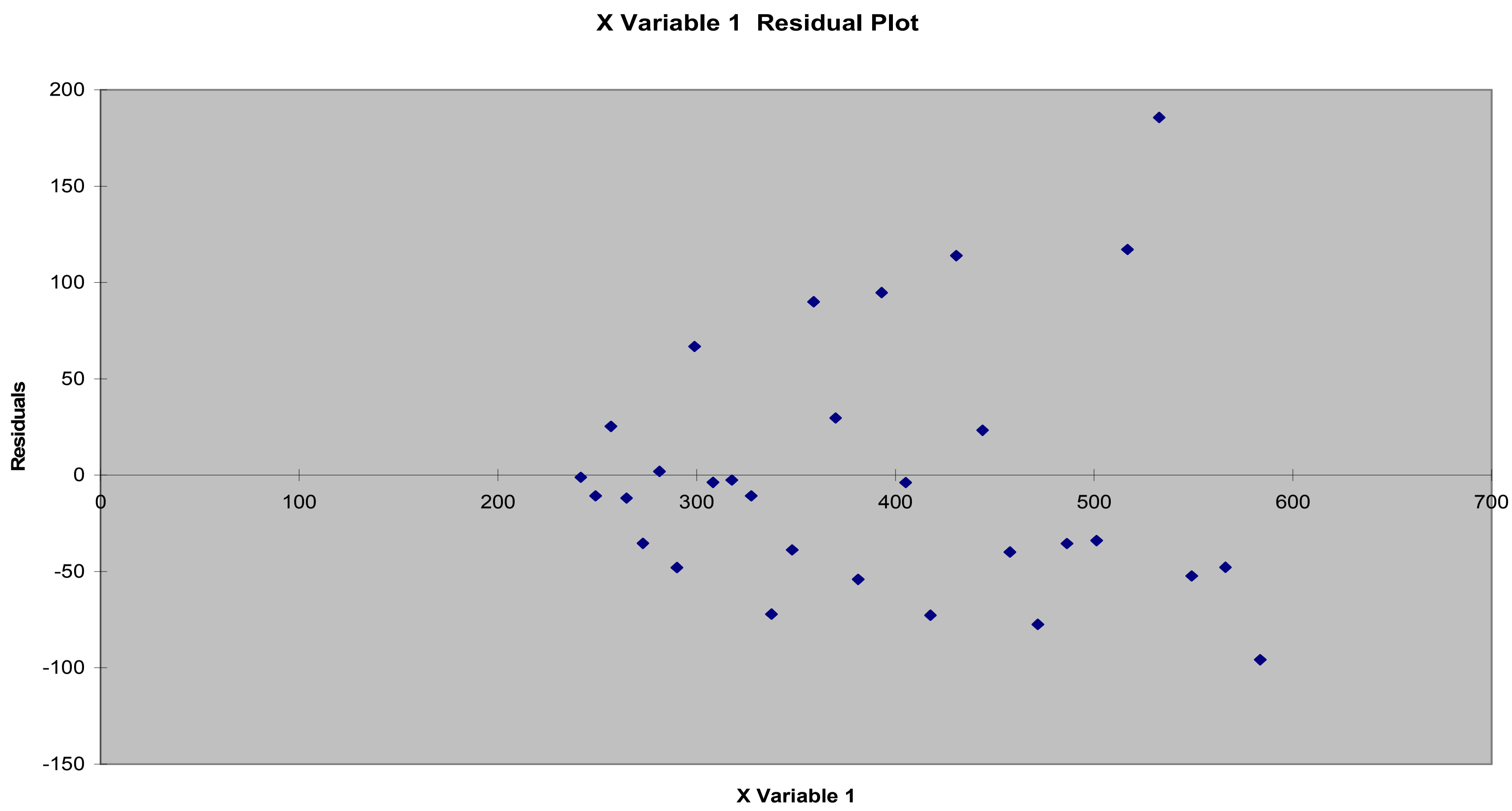
Regression Statistics	
Multiple R	0.848760596
R Square	0.72039455
Adjusted R Square	0.710408641
Standard Error	67.57521753
Observations	30

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	329425.886	329425.886	72.14110958	3.10369E-09
Residual	28	127859.4807	4566.410025		
Total	29	457285.3667			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	3.763774452	48.79779265	0.077130014	0.939068637	-96.19397118	103.7215201	-96.19397118	103.7215201
X Variable 1	1.031664682	0.121463881	8.493592266	3.10369E-09	0.782857204	1.280472161	0.782857204	1.280472161

Residual Plot for Failures versus Time (exp)



Regression Output for Failures versus Time and Rainfall

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.881585034
R Square	0.777192172
Adjusted R Square	0.760687888
Standard Error	61.4295017
Observations	30

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	355398.6073	177699.3037	47.09033	1.5742E-09
Residual	27	101886.7593	3773.583679		
Total	29	457285.3667			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	145.2588971	69.83287662	2.080093276	0.047137	1.973671436	288.5441228	1.973671436	288.5441228
X Variable 1	0.980004697	0.112159262	8.737617201	2.36E-09	0.749872903	1.210136491	0.749872903	1.210136491
X Variable 2	-0.206073742	0.078549047	-2.623504031	0.01414	-0.367243072	-0.044904412	-0.367243072	-0.044904412

Regression Output for Failures versus Time and Temperature

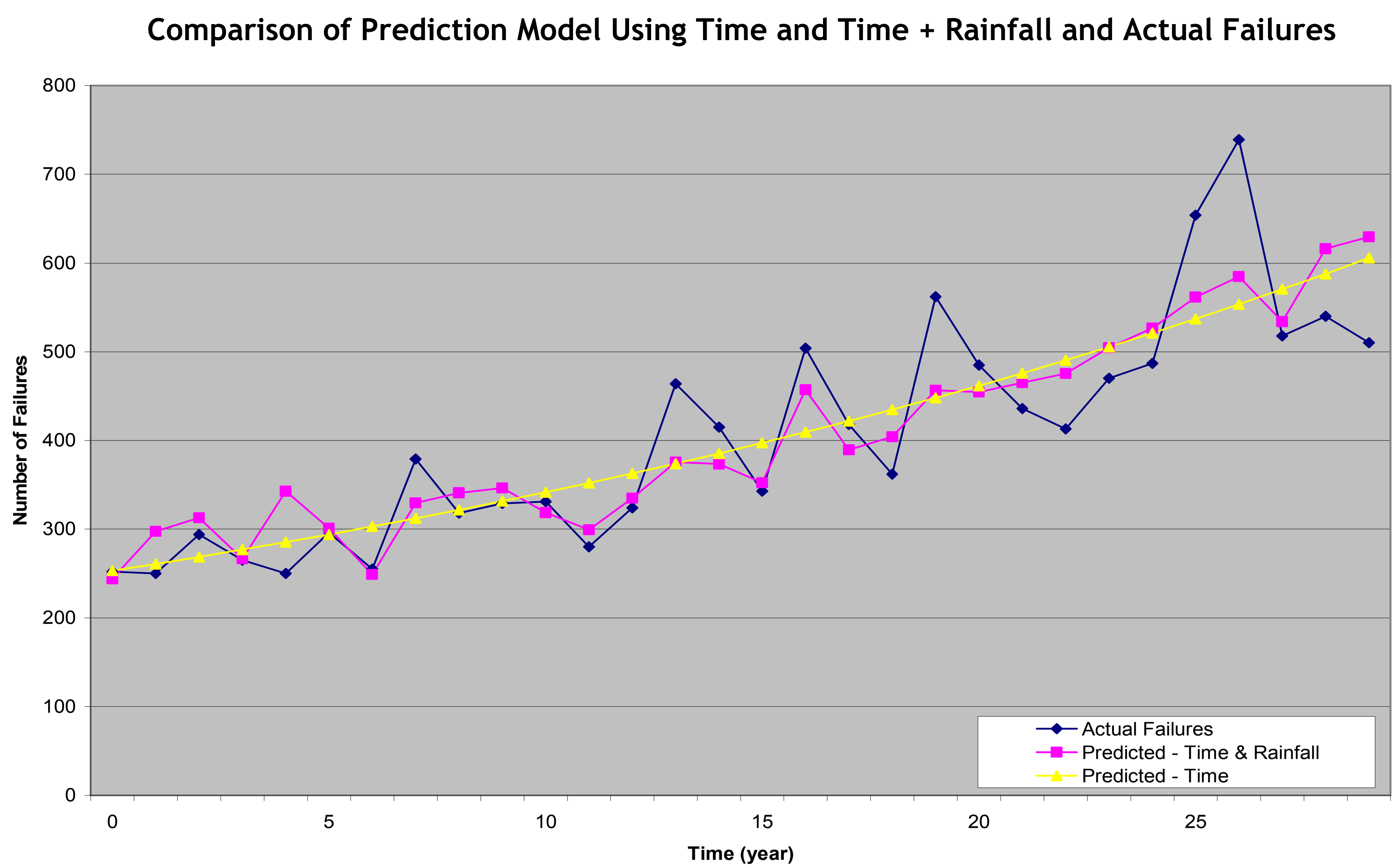
SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.849817
R Square	0.722189
Adjusted R Square	0.701611
Standard Error	68.594
Observations	30

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	330246.7	165123.3	35.09427	3.09E-08
Residual	27	127038.7	4705.137		
Total	29	457285.4			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-26.6623	88.09323	-0.30266	0.764468	-207.415	154.09	-207.415	154.09
X Variable 1	1.027637	0.123672	8.309389	6.43E-09	0.773883	1.28139	0.773883	1.28139
X Variable 2	0.350276	0.838652	0.417665	0.679495	-1.3705	2.071047	-1.3705	2.071047


Comparison of Prediction Model Using Time and Time + Rainfall and Actual Failures
Number of Failures
800
700
600
500
400
300
200
100
0
0
5
10
15
20
25
Time (year)
Actual Failures
Predicted - Time & Rainfall
Predicted - Time