Chapter 7.
Application of the General Break Regression Model (GBRM) to the Case Study Pipe Break Database

7.1 Introduction

In this chapter, the application of the general break regression model (GBRM) introduced in Section 4.7 to the study area pipe break database is presented. In particular the analytical solution in Eq. (4.8.2) is utilized to obtain the optimal replacement times. A comparison of replacement times between the Weibull proportional intensity model and the general break regression model is reported in Table 7.3. In addition, information on the indirect repair cost of pipe break is used in the optimal replacement analysis to consider the effects of including the indirect cost of repair on the replacement analysis. Replacement cost and direct cost of repair are shown in Table 5.3.

7.2 Indirect Cost of Repair

Indirect costs are not easily quantified as are the direct costs of repair. Given the uncertainties in estimating indirect costs, simple percentages are used to define indirect costs for the actual analyses. That is, indirect costs are assumed to be a certain percentage (e.g. 20% and 30% of the direct repair costs) of the direct costs of a given main break. However, a methodology on how to estimate indirect cost of repair is developed in this subsection as a possibility of future research and approximate estimates of the indirect cost obtained from the utility are presented in Table 7.1 as an example. These estimates indicate that indirect costs between $624 and $1281 can be supported, even without accounting for service disruption. This represents between 20% and 41% of the direct cost of a 6-inch water main break.

Indirect costs represent community-wide costs associated with a pipe break. These costs can be a measure of inconvenience or financial loss to the customer. Indirect costs of a pipe break can be defined more accurately as the cost that results from a break in the form of productivity loss, property damage, and injury [PPK Consultants (1993)].

Indirect cost can be grouped into the following categories: (1) value of water lost during a break incident, (2) liability to third parties, (3) traffic disruption, and (4) service disruption including loss of revenue for the customer and cost of alternate water supply.

Other less tangible issues that can be considered as costs in the optimal replacement analysis include the public image and perceptions and environmental impacts ("Identification of Critical Water Supply Assets," PPK Consultants, Research Report No. 57, Urban Water Research Association of Australia, June 1993).

Table 7.1 Example Indirect Costs for A 6-inch Pipe.

Indirect Cost Component	Estimated Range of Costs	
Value of lost water	$108	$216
Third party liability	$150	$150
Traffic disruption	$366	$915
Service disruption	Not estimated	Not estimated
Total	$624	$1281

7.2.1 Value of water lost

The value of water lost can be estimated from the Equation

$$Cost_W = Q * R_T * \$$$

where: Q = AV = flow rate, R_T = response time taken to be 4 hours, \$ = unit cost of water.

Flow rate can be determined by using assumed average velocity. Repair time may be used as response time in the equation. The discharge may be estimated by Q (GPM) = $16.05D^2$ for an assumed velocity of 7 ft/sec and D is the diameter in inches. For the utility company in the study area \$0.44/1,000 gallons was used as the unit cost of lost water. Therefore, the cost of lost water for a 6-inch main break is approximately \$108.

7.2.2 Liability to third parties

Third party liability can be defined as injury and /or damage to a person, object, enterprise or intangible. It can be expressed as:

$$Cost_{TPL} = F_L * \$_S$$

where, $Cost_{TPL}$ = cost of third party liability, F_L = locality factor taken to be 1, $\$_S$ = average third party liability cost for different main size.

The locality factor, F_L, may have a range with the maximum applying to a highly developed public area. According to the data provided the utility company of the study area, the total paid out amount on claims is obtained as \$305,355 (1997 cost). It was divided among the 2032 breaks occurred in 1997 to yield an average claims cost of \$150.

7.2.3 Traffic Disruption

Repair of a pipe break typically requires some intrusion into the roadway, and thus there is public inconvenience. Garber and Hoel (“Traffic and Highway Engineering”) give the following example for obtaining a cost estimate for traffic disruption. An arterial street with a mean traffic volume of 2,500 vehicles per day is considered (the range for arterial streets is 2,500 to 37,500). For a 2 minute delay per vehicle and value of time of \$15/hour during the 4-hour repair duration the cost is (2500 / 24) (4) (2 / 60) (15) = \$366. A 5-hour delay translates into a cost of \$915.

7.2.4 Service Disruption

Measuring service disruption resulting from a main break incident can be measured from the assumption that the disruption will have a slight negative effect on GDP (Gross Domestic Product) for various consumers. The type of consumer should be considered as:

a. Minor consumers - require water as an essential or fundamental resource for their operations (e.g. retail industry, domestic consumers who may have to purchase bottled water etc.)
b. Major consumers - require water for their normal operations (e.g. beverage industry, restaurants, etc.)

c. Critical consumers - supply is essential and who may suffer significant loss beyond the duration of the non-supply period as a consequence of failure (e.g. hospitals, oil refineries, etc.)

For critical consumers, there is an additional cost associated with a disruption of duration greater than a particular threshold. That is, the specific cost of closing down and restarting the operation once disruption has occurred, or the potential cost of a human life endangered by a disruption of water supply.

7.3 Optimal Replacement Analysis with the General Break Regression Model

In the analysis of optimal replacement with the general break regression model the following steps are adopted.

Step 1. Using the cost information compute the optimal threshold break rate, $\mathrm{Brk}_{\mathrm{th}}$. For example, using the cost data given in Table 5.3 we obtain (with the aid of Eq. (3.7.1)) the threshold break rate for 6-inch pipe with 1000 ft of length as

$$\mathrm{Brk_{th}} = \frac{\ln(1+\mathrm{R})}{\ln(1+\mathrm{C(repair)/F(replacement)})} = \frac{\ln(1+0.077)}{\ln(1+3120/(93*1000))}$$

$\mathrm{Brk}_{\mathrm{th}}$ = 2.25 breaks.

Step 2. The general break regression model for the cumulative number of breaks at time, t, denoted by $N_c(t)$ is

$$\mathrm{N_c(t) = (1 - WF)(Bl + Al(t - t_0)) + WF * Be * e^{Ae(t-t_0)}}$$

This equation is utilized for predicting future breaks. The optimal weighting factor, WF, is obtained by the optimization problem given in Section 4.3.1 and is reproduced here for convenience.

$$\min\ SSE = \sum_{j=1}^{n}\left(O_j - C_j\right)^2 \qquad (4.7.4)$$

Subject to:

$$C_j = (1 - w_i)L(t) + w_i E(t)$$

$$w_i = i \cdot e$$

where

$$i = \{0, 1, \ldots, 1/e\}$$

$1/e$ is an integer

$$0 < e < 1$$

where SSE = sum of squared errors for each i

O_j = each observed break time

C_j = computed value from the general model for each j

ω_i = weighting factor for each i

E(t) = the exponential model (Eq. (4.7.1))

L(t) = the linear model (Eq. (4.7.2))

n = number of breaks

Step 3. The optimal replacement time for a pipe is obtained by using the relationship of the cumulative number of breaks and the threshold break rate (Eq. (4.3.5)), that is

$$\frac{dN_c(t)}{dt} = Brk_{th}\,.$$

Therefore, the optimal replacement time, t*, is expressed as Eq. (4.8.1), that is

$$t^* = \frac{1}{Ae} \ln\left(\frac{Brk_{th} - (1 - WF)Al}{WF * Ae * Be * e^{-Ae^* t_0}} \right).$$

The search method introduced in Section 4.8 produces the same results. However, this method in Step 3 is used since using Eq. (4.8.2) is computationally more efficient to obtain the optimal replacement time.

Figure 7.1 shows the quality assurance (QA) and quality control (QC) process in developing the general break regression model. The break forecasting module, that is the general break regression model, relies on historic break data to predict future breaks for individual pipes. The break database provides almost all of the data used in this process. An Excel spreadsheet was developed to process the 32,242 records of data by eliminating irrelevant records and identifying inconsistent records. The spreadsheet then assigns a Pipe ID to each record, and generates a file used as input for the next step.

A separate MATLAB program, which is shown in Appendix D.9, performs the general break regression analysis for the breaks for each Pipe ID. It also performs the optimization algorithm described in Step 2. In order to conduct a representative regression analysis, at least three breaks must have occurred on the pipe. The model computes sum of residual errors for the general break regression, and selects the regression coefficients that yield the lowest sum of residual errors for use in subsequent steps of the modeling.

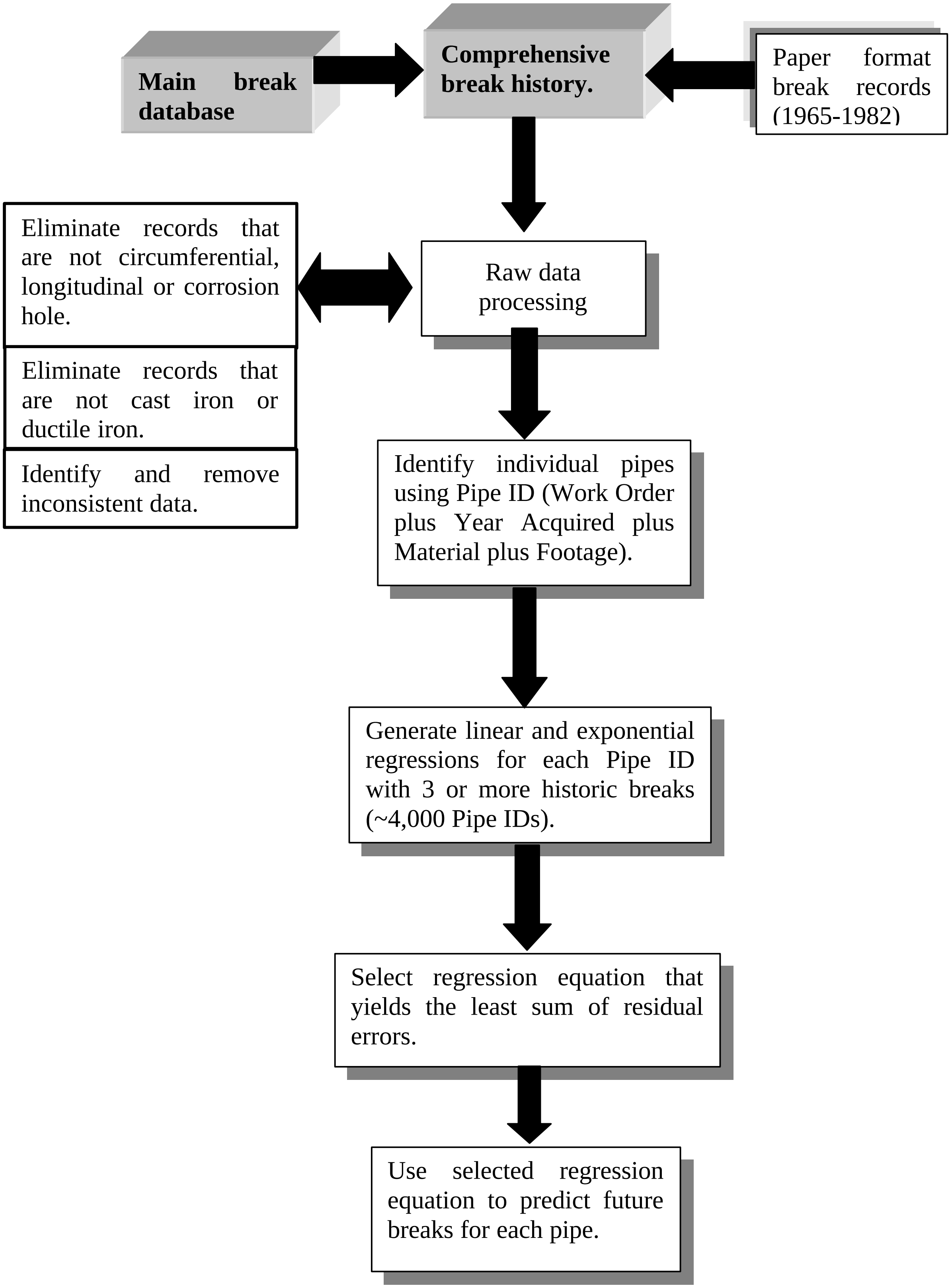

Figure 7.1 Break Forecasting Module Overview

The process of forecasting future main breaks highlights an important aspect of the modeling that is illustrated in Figure 7.2. The utility's distribution system includes over 4,000 miles of pipe, but not every pipe has experienced a break since 1983. Therefore, only about 1,840 miles of pipe are represented in the break database. Furthermore, of the 1,840 miles of pipe, only about 640 miles of pipe has experienced three or more main breaks needed to conduct the regression analyses. As a result, about 4000 pipes (Pipe IDs) have been identified for the optimal replacement analysis. This limits the amount of pipe included in the initial pool of potential replacement candidates. However, since the model can and should be re-applied at regular intervals, as pipes begin to fail multiple times the pool of potential replacement candidates will grow to include these pipes.

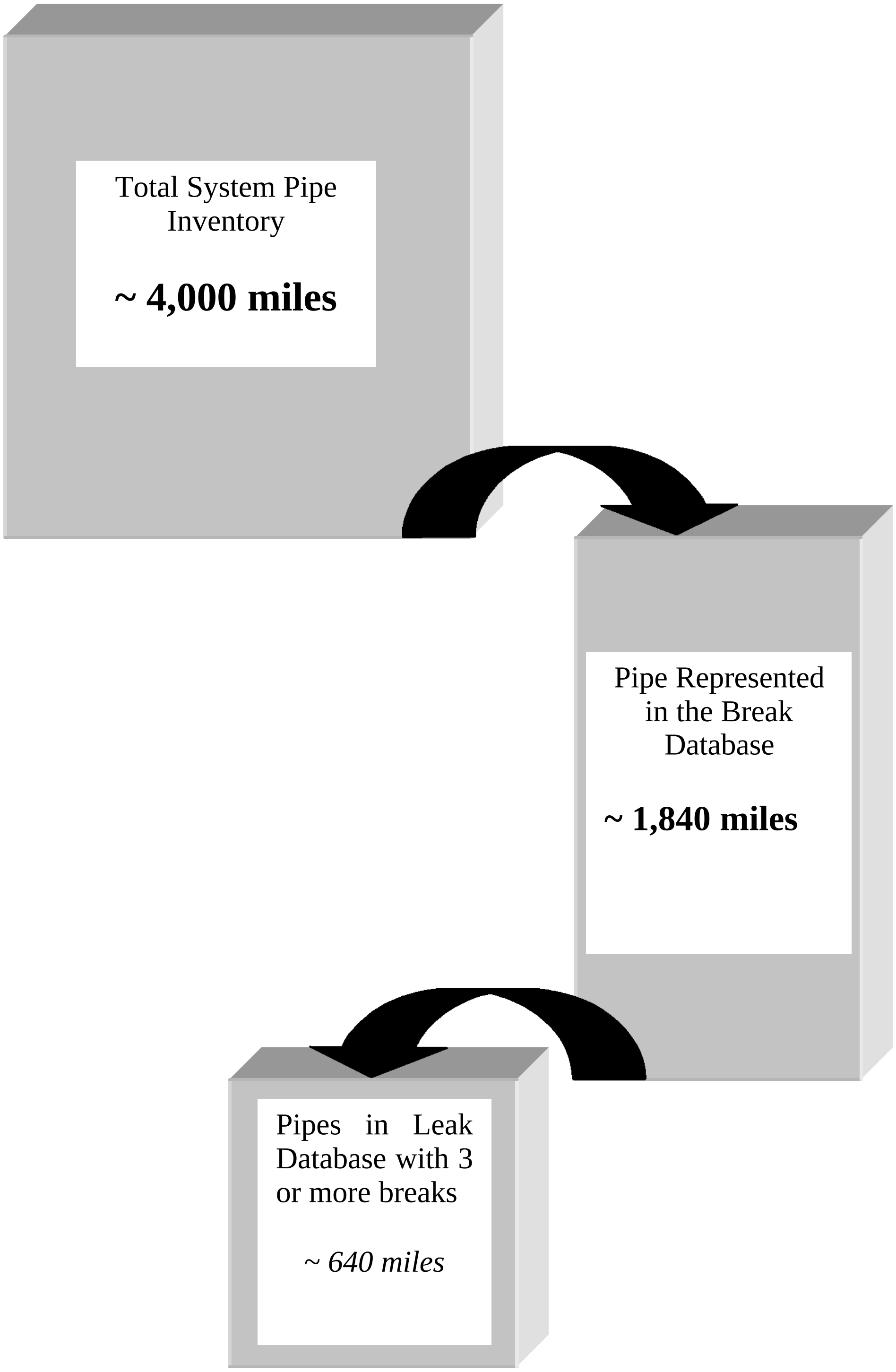

Figure 7.2 Development of Water Main Replacement Candidate Pool

7.3.1 Optimal Replacement Analysis Results

The objective of the modeling was to identify and prioritize cost-effective replacement of specific pipes, and to assess the impact of various renewal strategies. In this section the results of a series of optimal replacement analyses are presented by using the entire break database. The analyses are done by using the general break regression model with various cost options. This section also illustrates various replacement strategies that can be taken for practical replacement purposes. In addition comparison of the optimal replacement results by using the Weibull proportional intensity model and general break regression model for the break database (given in Appendix D.11) described in Section 6.2 is given in Subsection 7.3.3. The *complete break database* (Appendix D.11) consists of the pipes with complete break records from installation to current date (Dec. 1998). Discussions on the results are also provided in the subsection.

7.3.2 Results for the Various Cost Options

A Base Case was established as a point of comparison for all other runs. The Base Case included the following assumptions:

Pipe IDs with 3 or more historic breaks were included in the analysis.
Replacements start in 1999.
Installation and repair costs were discounted at the rate of 7.7%.
No allowance for escalation of costs (inflation) was included.
Indirect costs were not included.
The “REPLACED” field in the break database was not considered. Thus, some Pipe IDs that appear on the replacement list might have already been replaced, either partially or completely.

The results of three other model runs are presented along with the Base Case. The three model runs share the same basic assumptions as the Base Case, except as noted. The three runs are:

Indirect costs at 20% - In this model run the indirect costs of main breaks were set equal to 20% of the direct costs.
Indirect costs at 30% - In this model run the indirect costs of main breaks were set equal to 30% of the direct costs.
“REPLACED” field considered – In this model run all Pipe IDs where the “REPLACED” field in the Leak Database was “True” for any record were omitted from the pool of candidates for replacement.

The results of the four runs are summarized in Table 7.2. Replacement needs are greatest in the first year of the simulation, regardless of the assumptions used. This is due to pipes already experiencing break rates equal to or greater than the threshold break rates of their own, making them candidates for immediate replacement.

As noted earlier, the pool of candidate pipes for replacement was approximately 640 miles in length for the Base Case. Thus, in the Base Case run about one-third of the candidate pipes reach the end of their optimum economic life in the first five years.

Table 7.2 Summary of Modeling Results.

	Miles of Pipe to Be Replaced			
	Base Case	**Indirect Costs @ 20%**	**Indirect Costs @ 30%**	**"Replaced" Field Considered**
1999	146	173	181	119
2000	31	24	26	17
2001	20	16	18	16
2002	19	22	17	15
2003	14	12	13	9
First 5 year total	230	247	255	176
First 5 year average	46	49	51	35
30 year total	408	425	430	325
30 year average	14	14	14	11

It is important to understand the implications of the “REPLACED” field in the break database on the optimal replacement analysis results. The break database contains information related to water main breaks. If a Pipe ID has failed multiple times, the break database will have one record for each main break. The “REPLACED” field is True for a particular record if the portion of the Pipe ID where that break occurred was replaced. However, it is not possible to determine if the entire pipe or only a portion of the pipe was replaced. Because there is no pipe inventory database, the only way to determine the length of pipe replaced and its exact location is by manual research of the company’s paper files.

In terms of the optimal replacement analysis, the Base Case did not consider information in the break database relating to the “REPLACED” field. In other words, the Base Case might have identified a pipe for replacement that had already been replaced. On the other hand, the model run labeled “REPLACED Field Considered” did not include any Pipe ID from the replacement candidate pool if any of its break database records had the “REPLACED” field as True. Thus, for example, a 2,000-foot long pipe may have been removed from the candidate pool even if only a 100-feet segment of it had been replaced. Therefore, the “REPLACED Field Considered” run might have excluded some pipes that need to be replaced.

As a result, the true replacement need is somewhere between the results from the Base Case run and the “REPLACED Field Considered” run. As specific construction projects are planned using the prioritized replacement list, additional manual research will be necessary to determine if a pipe, or portions of the pipe, has already been replaced. This issue should be addressed in the company’s ongoing information management system upgrades, so that a real-time inventory of pipe in the system is maintained.

The model relies on historic main break data to project future main breaks, and hence associated repair costs, for individual Pipe IDs. As the system continues to age, it is likely that new pipes may begin to experience accelerated break rates and become candidates for replacement. Therefore, it is recommended that the replacement program should focus on the first five years of model results, and then use the model as a tool to revise replacement priorities at regular intervals.

7.3.3 Comparison of Results by the General Break Regression Model and the Weibull PIM

The results of the optimal replacement analysis by using the general break regression model (GBRM) for the break database used in Chapter 6 are presented in this subsection along with the results obtained by using the Weibull PIM for the same database. The sample results shown in Table 7.3 are based on the analyses using the replacement and the direct cost of repair. The complete results are presented in Appendix D.10. The plots of the general break regression model for the first five PIPE IDs in Table 7.3 are presented from Figure 7.3 to 7.7.

As can be seen from Table 7.3 the use of the Weibull PIM results in later replacement years than the general break regression model. Because both the models employ predicted break rates for replacement time computation it is hard to say which one is accurate. Clearly the Weibull PIM prediction is a low break rate compared to that of the GBRM. For a 1000 ft pipe, one year of postponement can result in an interest saving of $7,700 for $100,000 investment at 7.7% interest rate. Therefore, these models should be used only to rank order pipes for replacement in a candidates list. Actual replacement should occur with a repair or surface repaving or a region wide bulk replacement. Of course, such replacement times should be documented and compared with the model prediction for the efficiency.

Table 7.3 Sample of the Optimal Replacement Analysis Results by the Weibull PIM and the GBRM.

Pipe ID	Inst_YR (year)	Length (ft)	icpf ($/ft)	rcpb ($)	A_lin	B_lin	A_exp	B_exp	wf(1 = exp)	SREE	SREC	diff	t*(GBRM)	t*(WPIM)
2-1933-CI-12	1933	14691	116.05	7753	0.1678	-4.820862	0.05475	0.16108	1	0.67967	0.67967	0	2059	2091
14449-1952-CI-6	1952	1363.5	92.77	2814	0.38378	-8.648649	0.11736	0.06578	0.47	0.723796	0.295722	0.428074	2009	2041
13617-1951-CI-6	1951	371	92.77	2814	0.30132	-5.575849	0.08201	0.23745	0.3	5.289215	3.548829	1.740385	2008	2015
72-2550-1972-CI-6	1972	1768	92.77	2814	0.92586	-9.80666	0.16351	0.28815	0.65	11.413452	9.871874	1.541578	2002	2020
4194-1941-CI-6	1941	1381	92.77	2814	0.93745	-39.69251	0.14585	0.00406	1	20.281674	20.281674	0	2001	2010
01/04/29-1929-CI-6	1929	1985	92.77	2814	0.36458	-18.26047	0.15197	0.00021	0	1.649369	0.01888	1.630489	2014	2026
01/21/28-1928-CI-4	1928	1546	92.77	2362	0.34343	-16.53734	0.08039	0.02492	1	12.037961	12.037961	0	2023	2041
02/21/29-1929-CI-12	1929	5499	116.05	7753	0.86318	-39.45641	0.12079	0.00759	0.28	43.626863	5.369079	38.257784	2011	2052
03/07/29-1929-CI-6	1929	1797	92.77	2814	0.68532	-31.95959	0.10704	0.01122	0.79	10.568399	9.752046	0.816353	2006	2024
04/30/29-1929-CI-6	1929	1242	92.77	2814	1.06904	-50.02573	0.13124	0.00442	0.33	85.352599	9.980228	75.372372	2000	2012
05/01/29-1929-CI-12	1929	1609	116.05	7753	0.33333	-16.33333	0.09967	0.00776	1	1.247722	1.247722	0	2006	2005
06/01/22-1922-CI-12	1922	34750	116.05	7753	0.16393	-5.491803	0.08078	0.04277	0	1.519869	0.127385	1.392483	2089	2093
06/06/24-1924-CI-6	1924	1240	92.77	2814	0.26315	-13.63157	0.10505	0.00253	0	1.553339	0.01662	1.536718	2008	2014
06/14/29-1929-CI-6	1929	816	92.77	2814	1.07378	-35.79602	0.09095	0.11875	0	1568.69729	57.474849	1511.2244	2048	2025
06/17/27-1927-CI-6	1927	649	92.77	2814	0.35209	-15.92607	0.10257	0.00681	0	17.233122	1.340219	15.892903	2078	2026
07/17/29-1929-CI-6	1929	800	92.77	2814	0.51	-19.19555	0.09079	0.04788	0.31	21.033594	5.363337	15.670257	2005	2046

A_lin and B_lin : Coefficients of linear model

A_exp and B_exp : Coefficients of exponential model

wf : Weighting Factor

SREE : Sum of Residual Errors when only the exponential model is used

SREC : Sum of Residual Errors when the general break regression model is used

diff : Difference of SREE and SREC

t*(GBRM) : Optimal Replacement Year by GBRM

t*(WPIM) : Optimal Replacement Year by WPIM

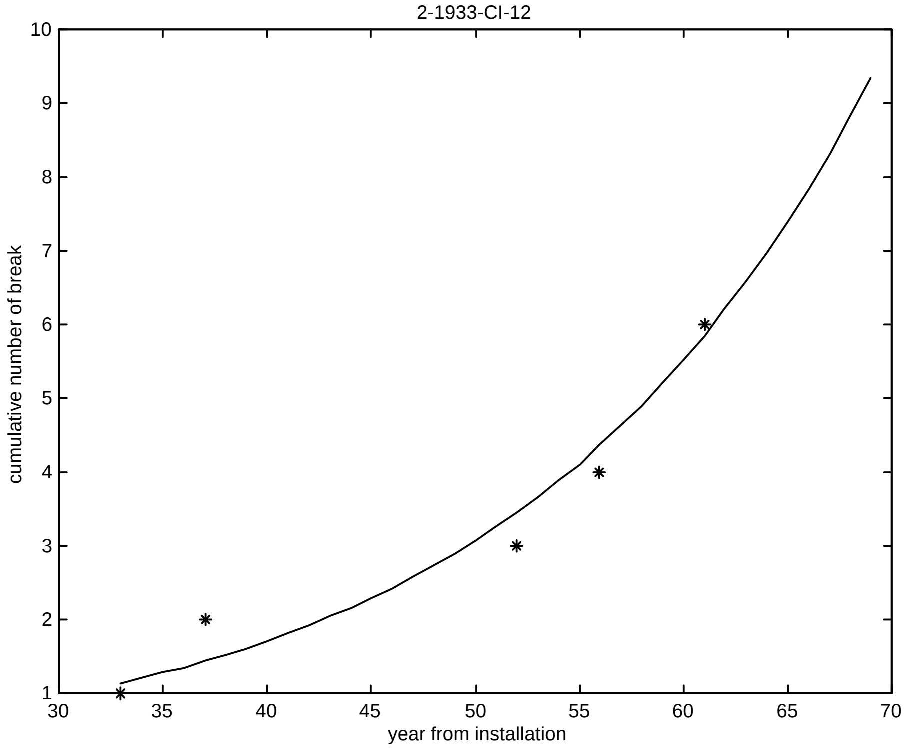

Figure 7.3 GBRM Plot for PIPE ID 2-1933-CI-12

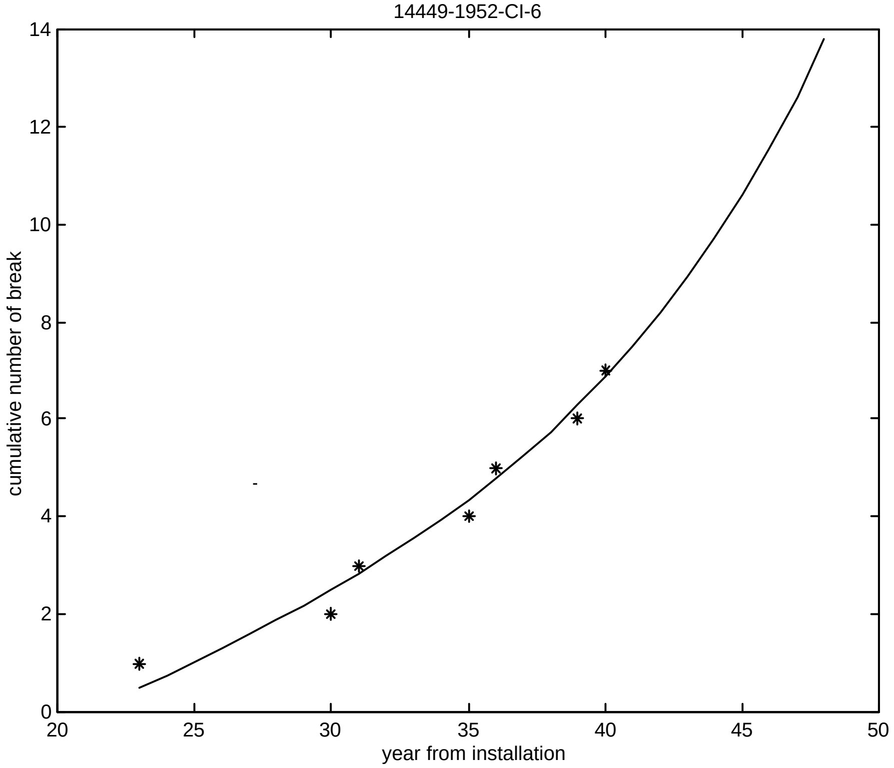

Figure 7.4 GBRM Plot for PIPE ID 14449-1952-CI-6

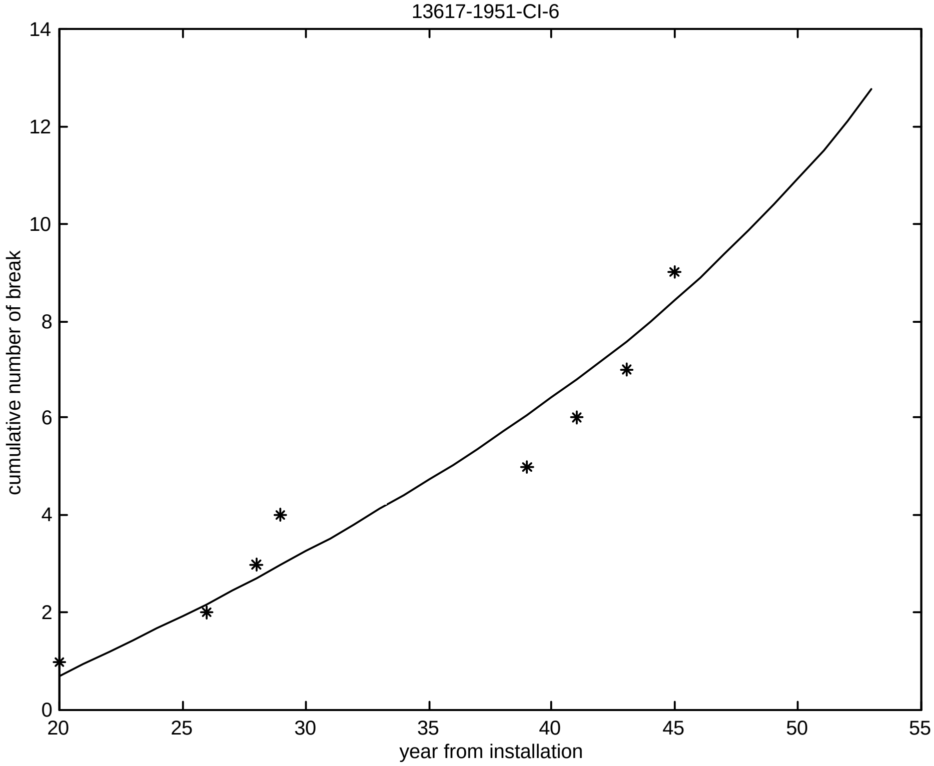

Figure 7.5 GBRM Plot for PIPE ID 13617-1951-CI-6

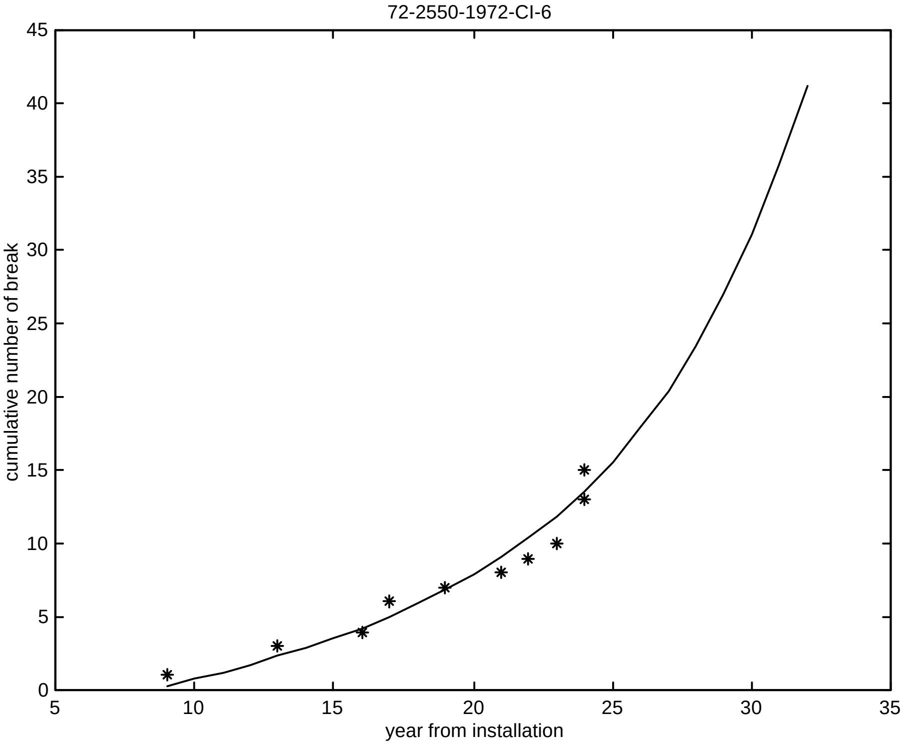

Figure 7.6 GBRM Plot for PIPE ID 72-2550-1972-CI-6

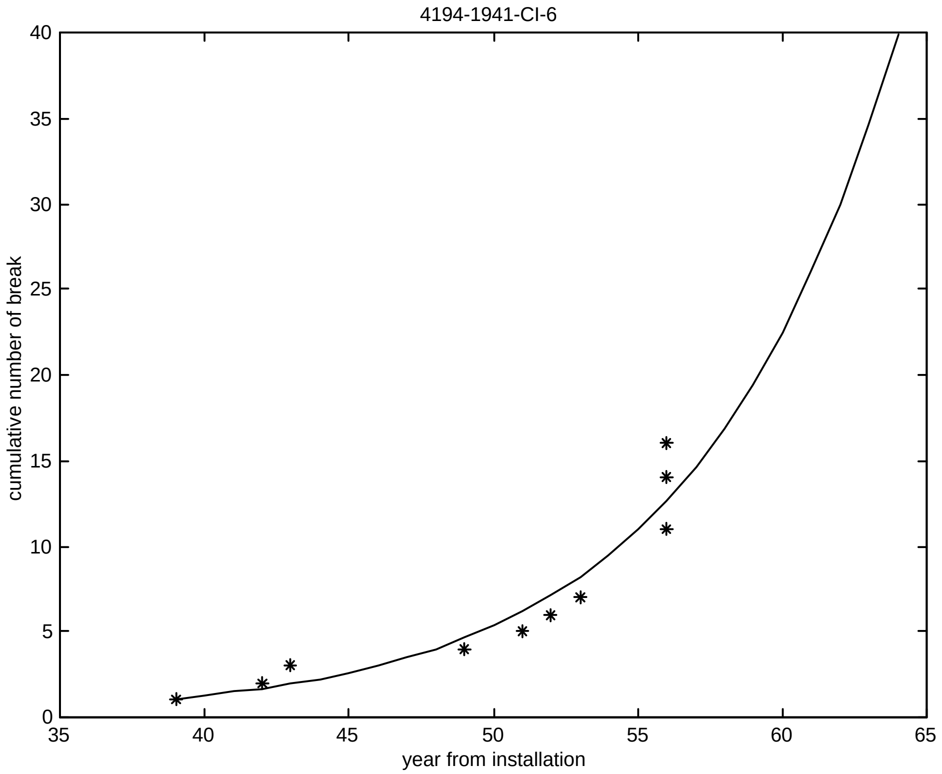

Figure 7.7 GBRM Plot for PIPE ID 4194-1941-CI-6

To illustrate how the Weibull PIM is established and the optimal replacement time is obtained for a pipe (PIPE ID), an example is shown below.

Example

By using the recorded historic break times obtain the general break regression model and the optimal replacement times of the pipe (PIPE ID) 14449-1952-CI-6. Use the interest rate as 7% per year.

Solution

The information on the properties of the pipe, 14449-1952-CI-6, obtained from the break database are as follows:

PIPE ID	Inst_Yr (year)	Length (ft)	icpf ($/ft)	rcpb ($)	Brk_th (breaks/year)
14449-1952-CI-6	1952	1363.5	92.77	2814	3.08

The recorded historic break times of the pipe, 14449-1952-CI-6, obtained from the break database are as follows;

MTB(1)	MTB(2)	MTB(3)	MTB(4)	MTB(5)	MTB(6)	MTB(7)	MTB(8)
277	361	373	426	437	469	480	546

The value in the parentheses after MTB (months to break from installation) provides the cumulative number of breaks at each MTB and the order of breaks.

First, the entire data (break times and corresponding cumulative number of breaks) are fitted to the linear model, that is

$y_i = A\_lin + B\_lin \cdot x_i + \varepsilon_i, \quad i = 1, 2, \ldots, n$

where

y_i = the cumulative number of breaks at ith break

x = the time of ith break (year)

ε_i = error at ith break

and n = total number of breaks of a pipe

The method of least squares is used to estimate A_lin and B_lin. Estimates of A_lin and B_lin are obtained by solving equation

$$A\_lin = \overline{y} - B\_lin \cdot \overline{x} \tag{7.1}$$

where

$$\overline{y} = \frac{1}{n}\sum_{i=1}^{n} y_i \text{ and } \overline{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \, .$$

Estimate of B_lin is obtained by solving equation

$$B\_lin = \frac{S_{xy}}{S_{xx}}$$

where

$$S_{xx} = \sum_{i=1}^{n} (x_i - \overline{x})^2 \text{ and } S_{xy} = \sum_{i=1}^{n} y_i (x_i - \overline{x})^2 \, .$$

The ith residual error is

$\varepsilon_i = y_i - (A\_lin + B\_lin\ x_i), \quad i = 1, 2, \ldots, n$

The error sum of squares is expressed as

$$SS_E = \sum_{i=1}^{n} \varepsilon_i{}^2 = \sum_{i=1}^{n} (y_i - \hat{y}_i)^2 \, .$$

The estimated values of A_lin and B_lin for the pipe, 14449-1952-CI-6, are

A_lin = 0.378 and B_lin = -8.65.

Second, the entire data is fitted to the exponential model, that is

$y_i = B\_exp \cdot x_i^{A\_exp} + e_i, \quad i = 1, 2, \ldots, n$

By natural logarithms to both sides we obtain a linear model, that is

$\ln(y_i) = \ln(B\_exp) + A\_exp \ln(x_i)$.

Let ln (B_exp) = a and A_exp = b, then the estimates of B_exp and A_exp are obtained by solving

$$a = \ln y - b \cdot \ln x \, . \tag{7.2}$$

Therefore, by substituting x for ln x and y for ln y in Eq. (7.2) and from Eq. (7.1) we obtain the estimates of A_exp and B_exp as

A_exp = 0.117 and B_exp = 0.0676.

Third, the error sum of squares in later 1/3 of break data points (e.g. calculate the residual error starting from 6th break if a pipe has total 9 breaks) are calculated by varying the weighting factor (e.g. from 0 to 1 by an increment of 0.01) in the general break regression model. The general break regression model for the pipe by using the estimated coefficients are expressed as

$$y_i = (1 - wf)\,(A\_lin + B\_lin \cdot x_i) + wf \cdot B\_exp \cdot e^{A\_exp \cdot x_i}$$

$$= (1 - wf)\,(0.378 - 8.65 \cdot x_i) + wf \cdot 0.0676 \cdot e^{0.117 \cdot x_i}$$

where i = 6, 7, 8. Since n = 8 for the pipe, 8/3 $\cong$ 3. Therefore, take the later 3 break data and calculate the error sum of squares for x_6 = 469, x_7 = 480, and x_8 = 546. The table below shows the estimated error sum of squares for each weighting factor value.

wf	SSE	wf	SSE	wf	SSE	wf	SSE
0	0.6362	0.25	0.3708	0.5	0.297	0.75	0.4146
0.01	0.6219	0.26	0.3642	0.51	0.298	0.76	0.4233
0.02	0.608	0.27	0.3579	0.52	0.2993	0.77	0.4323
0.03	0.5943	0.28	0.3519	0.53	0.301	0.78	0.4416
0.04	0.5809	0.29	0.3461	0.54	0.3029	0.79	0.4512
0.05	0.5678	0.3	0.3407	0.55	0.3052	0.8	0.4611
0.06	0.5551	0.31	0.3356	0.56	0.3077	0.81	0.4714
0.07	0.5426	0.32	0.3309	0.57	0.3106	0.82	0.4819
0.08	0.5305	0.33	0.3264	0.58	0.3138	0.83	0.4927
0.09	0.5186	0.34	0.3222	0.59	0.3173	0.84	0.5039
0.1	0.5071	0.35	0.3183	0.6	0.321	0.85	0.5153
0.11	0.4959	0.36	0.3147	0.61	0.3251	0.86	0.5271
0.12	0.4849	0.37	0.3115	0.62	0.3295	0.87	0.5391
0.13	0.4743	0.38	0.3085	0.63	0.3342	0.88	0.5515
0.14	0.464	0.39	0.3059	0.64	0.3393	0.89	0.5642
0.15	0.454	0.4	0.3035	0.65	0.3446	0.9	0.5771
0.16	0.4443	0.41	0.3015	0.66	0.3502	0.91	0.5904
0.17	0.4349	0.42	0.2998	0.67	0.3561	0.92	0.604
0.18	0.4258	0.43	0.2983	0.68	0.3624	0.93	0.6179
0.19	0.4171	0.44	0.2972	0.69	0.3689	0.94	0.6321
0.2	0.4086	0.45	0.2964	0.7	0.3758	0.95	0.6466
0.21	0.4004	0.46	0.2959	0.71	0.3829	0.96	0.6615
0.22	0.3926	**0.47**	**0.2957**	0.72	0.3904	0.97	0.6766
0.23	0.385	0.48	0.2958	0.73	0.3982	0.98	0.692
0.24	0.3778	0.49	0.2962	0.74	0.4062	0.99	0.7078
						1	0.7238

From the table we find that the error sum of square is minimum when the weighting factor (wf) is 0.47. Therefore, the general break regression model for the pipe is

$$y = 0.53\,(0.378 - 8.65 \cdot x) + 0.32 \cdot e^{0.117 \cdot x}$$

The optimal replacement time of the pipe is obtained by using Eq. (4.8.2), that is

$$t_1^* = \frac{1}{A\_exp}\ln\left(\frac{Brk_{th} - (1-WF)A\_lin}{WF * A\_exp * B\_exp * e^{-A\_exp * t_0}}\right) = \frac{1}{0.117}\ln\left(\frac{3.08-(1-0.47)0.378}{0.47\times 0.117\times 0.0676\times e^{-0.117*0}}\right) \cong 57$$

Since installation year is used as time ‘0’ in this calculation, actual replacement year is expressed as t* = [installation year] + t_1* = 1952 + 57 = 2009.

Figure 7.8 shows the plot of the resulting general break regression model of the pipe. It also shows the plots of the exponential and the linear model.

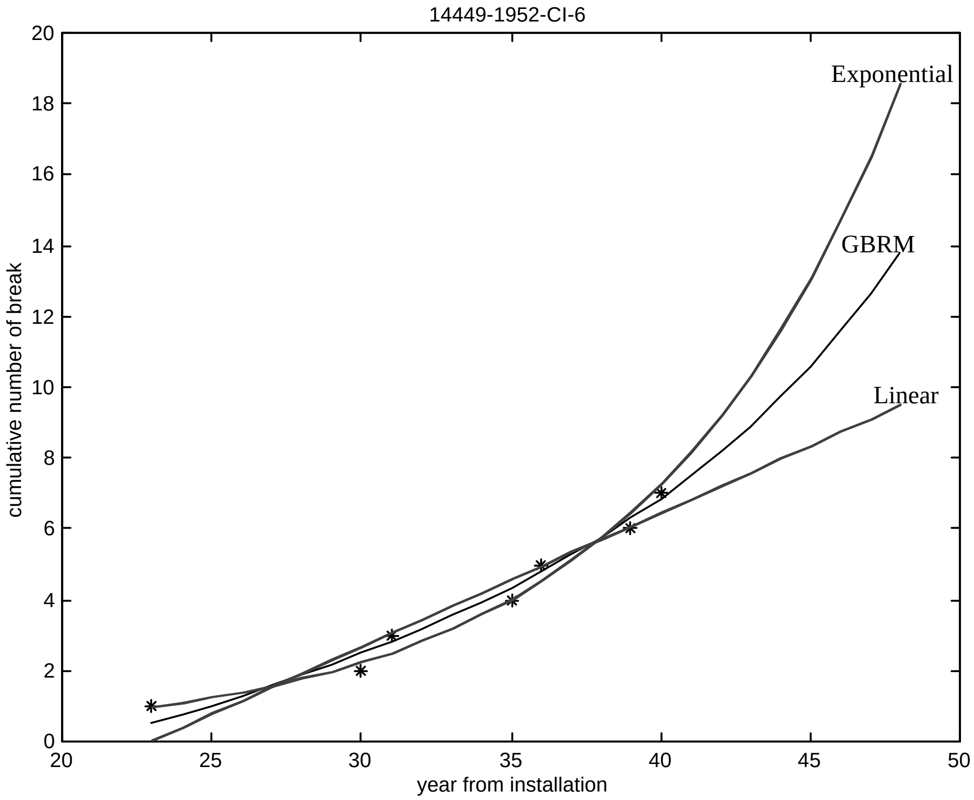

Figure 7.8 Break Versus Time Plots of the GBRM, Exponential and Linear Models

7.3.4 Replacement Strategy Evaluation

The optimal replacement analysis provides a prioritized list of pipes (by Pipe ID) to be replaced in order to minimize the total present worth costs associated with each pipe (cumulative cost of repairs plus replacement). Sometimes though, it may not be practical to replace pipes exactly according to the schedule that the optimal replacement analysis suggests. Therefore, the following strategies can be considered:

Strategy 1 : Replace pipes following the optimal replacement analysis's annual replacement prediction. The optimal replacement analysis determines the economically optimal time to replace a pipe. A strategy to replace pipes according to the schedule resulting from the model should, therefore, result in the most cost-effective program. However, in this strategy the recommended replacement projections are not practical, as the model identifies over 100 miles of pipe that should be replaced immediately (Table 7.2). In subsequent years, the replacement mileage drops into the tens of miles per year. It is impractical for a company to both commit the financial resources needed for the initial year, and to physically replace that amount of pipe in one year. Furthermore, it is also not practical to obtain and mobilize the resources for the initial year, then drastically reduce these resources to continue the replacement program in the following years. Therefore, this strategy is not recommended for consideration.

Strategy 2 : Replace pipe at the current rate of approximately $7 million per year. The current replacement budget of approximately $7 million per year represents about 13 miles of replacement. At this rate, it would take over ten years to simply replace the amount of pipe the optimal replacement analysis indicates needs to be replaced in the first year. It should be noted that Strategy 2 could have used any levels of replacement up to the uniform five-year levels defined in Strategy 3. Replacement of approximately 13 miles per year was selected solely for comparison purposes with the company's ongoing program.

Strategy 3 : Replace pipe at a fixed annual replacement rate over five years with a goal of replacing the cumulative five-year optimal replacement analysis predictions. Thus, a program of 46 miles of replacement per year would be required. As discussed earlier, if the "REPLACED" field is considered, the actual replacement may be as low as 35 miles per year. Replacement of pipes at levels greater than 230 miles over the five years could be considered if some indirect costs are also included. Additional replacement might be justified by the other non-economic considerations described in Section 5.41.

Based upon the findings of the optimal replacement analyses, it is concluded that the mileage of replacement should be increased from its current level of approximately 13 miles per year to as much as 46 miles per year over the next five years. This strategy targets pipes that have reached the end of their economic life, is practical to implement since it involves a consistent level of activity, and reduces the number of water main breaks in pipes with previous break history. The actual amount of pipe to be replaced may vary from the recommended 46 miles due to impact of previously replaced pipe (the "REPLACED" field issue) and the need to replace pipe for other non-economic reasons (for example, replace a pipe according to a repavement schedule). It is also concluded that the optimal pipe replacement analysis should be conducted at regular intervals (say 5 years) to refine the pipe replacement prioritization.

Another aspect to consider in actual application of the optimal replacement analysis is the issue of replacing a partial section of a pipe. Even though the analysis results in recommending replacement for the entire length of a PIPE ID, it is possible that practicing engineers can identify a problematic section of the pipe and they decide to replace only that section with frequent breaks. In such a case a different PIPE ID should be assigned for the replaced section and the remaining section of the previous PIPE ID. The section with new id should have all the past break history erased while for the other section with the older PIPE ID all data should be preserved.

Chapter 8.
Summary

The main contribution of this research consists of the successful development of new methodologies for determining optimal replacement times for individual pipes in water distribution systems. Given the fact that techniques in the past have failed to provide universal and analytical solutions to the optimal replacement time problem, the results of this work should have a positive influence in the way current repair and replacement decisions are made.

The proposed optimal threshold break rate is strictly analytical and provides a sustainable critical break rate. Moreover, generalizations to the functions of reliability theory such as the rate of occurrence of failure (ROCOF) and hazard rate are established. Even more crucial is the establishment of the empirical ROCOF function as $1/\Delta t_n$ (Δt_n is the time (n-1)th and nth break), which is precisely the same as the optimal break rate. This general relationship provides a sound theoretical framework in the sense that any ROCOF function that fits the data can be equated with the proposed threshold break rate to obtain the optimal replacement time. It is also established that the hazard function interpretation can be applied if the time between breaks is considered as the failure time. It has the interpretation of only survivor facing extinction. Currently in reliability theory there are more parametric models for the hazard function than for the ROCOF function.

The design aids in the form of a table (Table 3.3) and graphs (Figure 3.5 and 3.6) should permit engineers to draw quick inference on the replacement decisions regarding individual pipes. The methodology in Section 3.7 is established in such a way that practical threshold break rate tables and figures similar to Table 3.3, Figure 3.5 and 3.6 can be generated by any utility by using the diameter and the repair and replacement cost ratio for its system.

The Weibull proportional intensity model (PIM) provides an overall good fit to the pipe break data. It is anticipated that when high quality data are gathered, the method should yield accurate replacement times. In this dissertation a sound analytical approach is laid out. It is shown that the proportional hazards model (PHM) can be well modeled by categorizing the pipes with the same number of previous breaks and pipe material. It is found that ductile Iron pipes have a constant hazard after 2 breaks and cast iron pipes have a constant hazard after 1 break. Although this specific hazard characteristics of the pipes would be unique to the site considered, the general trend of having a constant hazard after certain critical number of breaks should hold for pipes in other systems as well.

An application of the optimal replacement analysis using the general break regression model for the study area break database is also presented. Various analyses based on different cost scenarios have been performed and practical implications of the results in terms of yearly replacement mileage are discussed. Although the specific discussions on how to actually implement the results from the optimal replacement analyses essentially applies only to the study area considered, other systems would also have similar limitations in actually applying the results. Therefore, the strategies outlined in Section 7.3.3 can be a guideline in actual implementation of optimal replacement analyses for other water distribution systems. The results of the optimal replacement analysis using the general break regression model are compared to the ones using the

Weibull PIM. The use of the Weibull PIM resulted in later replacement years than the general break regression model due to the difference in the structure of the two models. Since the Weibull PIM is based on the break rate between subsequent breaks which is highly variable, the Weibull PIM underestimated the break rate of pipe at a given time and resulted in later replacement years than the general break regression model. Also, the methodologies to estimate the indirect cost of pipe breaks are introduced in this research. Indirect costs of repair are categorized into four groups: value of water lost, liability to third parties, traffic disruption, and water supply service disruption. Among these four groups of indirect costs, water supply service disruption should be considered as the most important factor in estimating the indirect cost since it will have the greatest impact on the community's health and welfare.

The threshold break rate provides the most economical break rate beyond which the repair costs are more frequent recommending to take advantage of the slow break rate from a replaced pipe. This concept may be appealing to the water utilities because of the cost factors involved. The dual aspect of this approach is to assess the physically occurring break rate in the system. The main advantages with the proportional intensity model are: (i) it provides a pipe by pipe break rate; (ii) it provides a time dependent behavior, and (iii) it includes the environmental factors that influence the break rate process. We anticipate novel improvements in the third characteristic.

It is also recommended that, after prioritizing pipes for replacement based on the optimal replacement times, one need not follow these times precisely. However, replace pipes at an acceptable rate following the priority list coupled with other practical constraints in addition to the budgetary limit. If this sustainable replacement strategy does not address the problem well, clearly one has to increase the number of miles of pipes to be replaced.

REFERENCES

Andreou, S. A., D. H. Marks, and R. M. Clark. A new methodology for modeling break failure patterns in deteriorating water distribution systems: Applications, Advances in Water Resources, 10, 11-20, 1987b.

Andreou, S. A., D. H. Marks, and R. M. Clark. A new methodology for modeling break failure patterns in deteriorating water distribution systems: Theory, Advances in Water Resources, 10, 2-10, 1987a.

Ascher, H. and H. Feingold (1984), Repairable Systems Reliability, New York: Marcel Dekker, Inc.

Basalo, C., Water and Gas Mains Corrosion, Degradation and Protection, Ellis Horwood, Chichester, England, 1992.

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

Cohen, A., and Fielding, M.B., "Prediction of Frost Depth: Protecting Underground Pipes", Journal of American Water Works Association, 71:2, pp.113-116, 1979.

Das, B. M., (1990), Principles of Geotechnical Engineering, Boston, PWS-KENT.

Deb, A.K., Hasit, Y.J., Grablutz, F.M., and Herz, R.K., "Quantifying Future Rehabilitation and Replacement Needs of Watermains", Report to the American Water Works Association Research Foundation, 1997.

Duan, N.L., L.W. Mays, and K.E. Lansey, "Optimal Reliability based Design of Pumping and Distribution systems", Journal of Hydraulic Engineering, ASCE, 116(2), 1990.

Fielding, M. B., and Cohen, A., "Prediction of Pipeline Frost Load", Journal of American Water Works Association, 80:11, pp.62-69, 1988.

Freeze, R. A. and Cherry, J. A., (1979), Groundwater, Engelwood Cliffs, Prentice-Hall, Inc.

Goulter, I. C., and A. Kazemi, Spatial and temporal groupings of water main pipe breakage in Winnipeg, Canadian Journal of Civil Engineering, 15, 91-97, 1988.

Goulter, I. C., J. Davidson, and P. Jacobs, Predicting water-main breakage rate, Journal of Water Resources Planning and Management, ASCE, 119, 419-436, 1993.

Habibian, A., "Effect of Temperature Changes on Water Main Breaks", Journal of Transportation Engineering, ASCE, 120(2), pp. 312-321,1994.

Kalbfleisch, J. D. and R. L Prentice, The Statistical Analysis of Failure Time Data, New York: John Wiley & Sons, Inc., 1980.

Karaa, F.A., D.H. Marks, and and R.M. Clark, "Budgeting of Water Distribution Improvement Projects", Journal of Water Distribution Planning and Management, ASCE, 113(3), 1987.

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

Kleiner, Y., B. J. Adams, and J. S. Rogers, Long-term planning methodology for water distribution system rehabilitation, Water Resources Research, 34, 2039-2051, 1998a

Kleiner, Y., B. J. Adams, and J. S. Rogers, Selecting and scheduling rehabilitation alternatives, Water Resources Research, 34, 2053-2061, 1998b

Kumar, A., Bergerhouse,M., and Blyth, M.," Implementation of a Pipe Corrosion Management System", Corrosion ‘87, Moscone Center/San Francisco, California, Paper No. 312, March, 1987.

Kumar, A., Riggs, W., and Blyth, M., "Demonstration of the Pipe Corrosion Management System", Corrosion Mitigation and Management System, US Army Corps of Engineers, Construction Engineering Research Laboratory, Technical Report M-86/08, April 1986.

Kumar,A., Meronyk,E., and Segan, E., "Development of Concepts for Corrosion Assessment and Evaluation of Underground Pipelines", Technical Report M-337, Construction Engineering Research Laboratory, April 1984.

Lansey, K. E., and Mays, L. W., "Optimization Model Design of Water Distribution System Design", Journal of Hydraulic Engineering, ASCE, 115(10), 1989.

Lawless, J. F., Statistical Models and Methods for Lifetime Data, Wiley, New York, 1982.

Loganathan, G. V., Greene, J.J and Ahn, T., "A Design Heuristic for Globally Minimum Cost Water Distribution Systems," Journal of Water Resources Planning and Management, ASCE, 121(2), pp. 182-192, 1995.

Loganathan, G. V., Sherali, H. D., and Shah, M. P., "A Two-Phase Network Design Heuristic for the Minimum Cost Water Distribution Systems under a Reliability Constraints", Engineering Optimization, Vol. 15, 1990.

Male, J. W., T. M. Walski, and A. H. Slutski, Analyzing Water Main Replacement Policies, Journal of Water Resources Planning and Management, ASCE, 116, 363-374, 1990

Marks, H. D., et al., Predicting urban water distribution maintenance strategies: A case study of New Haven, Connecticut, Coop. Agreement R810558-01-0, Massachusetts Institute of Technology, Sponsored Project 94211, USEPA, Jan. 1985.

Mavin,K., "Predicting the Failure Performance of Individual Water Mains", Research Report No. 114, Urban Water Research Association of Australia, July 1996, ISBN 1876088176.

Mays, L., Water Distribution Systems Handbook, McGraw Hill, 2000

O’Day, D.K. Organizing and Analyzing Leak and Break Data for Making Main Replacement Decisions. Journal of American Water Works Association, 108:5:243 (1982).

Park, H., and J.C. Liebman, " Redundancy Constrained Minimum Cost Design of Water Distribution Nets", Journal of Water Distribution Systems Planning and Management, ASCE, 119(1), 1993.

PPK Consultants Pty Ltd, "Identification of Critical Water Supply Assets", Research Report No. 57, Urban Water Research Association of Australia, Sydney, New South Wales, 1993

Romanoff, M, "Underground Corrosion", National Bureau of Standards Circular 579, US Government Printing Office, 1957.

Rossum, J.R., "Predicting of Pitting Rates in Ferrous Metals from Soil Parameters", Journal of American Water Works Association, 69:6, pp.305-310, 1969.

Shamir, U., and C. D. D. Howard, An analytic approach to scheduling pipe replacement, Journal of American Water Works Association, 71, 248-258, 1979.

Sherali, H.D., Totlani, R., and Loganathan,"Enhanced Lower Bounds for the Global Optimization of Water Distribution Networks", Water Resources Research, 34(7), July 1998.

Su, Y.C., L.W. Mays, and K.E. Lansey, "Reliability Based Optimization Model for Water Distribution systems", Journal of Hydraulic Engineering, ASCE, 114(12), 1987.

US Pipe and Foundry Co., "An Attempt at Explaining Why Pipe Failures Increase under Certain Winter Conditions", Memorandum of Record, March 19, 1962.

Wagner, J.M., U. Shamir, and D.H. Marks, " Water Distribution Reliability", Journal of Water Resources Planning and Management, ASCE, 114(3), 1988.

Walski, T. M., and A. Pelliccia, "Economic Analysis of Water Main Breaks," Journal of American Water Works Association, 74(3), 140 – 147 (1982)

Walski, T. M., Replacement rules for water mains, Journal of American Water Works Association, 79, 33-37, 1987.

Walski, T.M. and Pelliccia, “An Economic Analysis of Water Main Breaks,” Journal of American Water Works Association, 74:3:140 (Mar. 1982).

Wedge, R .F., "Evaluating Thermal Pressure Changes In Liquid Packed Piping", in Pipeline Design and Installation, edited by K.K. Kienow., ASCE, Las Vegas, 1990,pp.80-94.

Woodburn, J., K. E. Lansey, and L. W. Mays, Model for the optimal rehabilitation and replacement of water distribution system components, paper presented at ASCE 1987 National Conference on Hydraulic Engineering, ASCE, Williamsburg, Va., 1987.