A Rational Basis for Making
Pipeline Replacement Decisions

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Introduction

Until relatively recently, the biggest problem faced by water providers in maintaining an adequate water distribution system was installation of new mains to keep up with development. This was because the bulk of water distribution infrastructure in the United States had been installed since 1900 and was still young. The issue of age deterioration did not become apparent until the 1960s. By the early 1980s, the need for massive pipeline replacements was perceived as a national issue with immediate action deemed essential to prevent a general collapse of the water delivery system nationwide. The November 1982 issue of the Journal of the American Water Works Association (1) was dedicated to rehabilitating distribution systems, citing the need for expenditures of \$75-\$110 billion over the next 20 years for that purpose. In May 2001 AWWA published "Dawn of the Replacement Era-Reinvesting in Drinking Water Infrastructure" (2). This document indicates that water utilities have generally deferred the inevitable replacement of their distribution infrastructure resulting in a potentially heavy financial burden (\$250 billion over 30 years) that will have to be met just to maintain the current level of service. These costs are over-and-above anticipated additional costs associated with regulatory compliance. These conclusions were largely derived from an analysis of the ages of pipes in service in 20 large utilities compared with estimated average life expectancies. However, while drawing attention to the possibility of major financial impacts on utilities and their customers, no guidance is offered to utility managers in deciding which pipes to replace in what order.

Beginning in the late 1960s, journal articles began to appear that addressed the problem of selecting pipes for replacement on a rational basis (3) (4) (5) (6). These articles presented various procedures for assessing pipe replacement priorities using statistical methods. Attempts to establish replacement decision-making rules by comparing replacement cost to the cost of repairs were made. Attempts were also made to identify generalized correlations among factors such as age, soil type, quality of construction, and traffic loading on streets overlying pipes. In general, these studies indicated that, although age is a factor, the intuitive sense that the oldest pipes should always be replaced first because they are naturally in the worst condition is not born out by experience. Neither is the idea that once a pipe reaches a certain age its failure rate will automatically increase to the point where replacement cannot be deferred, presenting the possibility that, at some point in time, replacement of massive amounts of pipe will be necessary to prevent the collapse of the system. Further, most utilities did not have sufficiently detailed records or resources to support complex statistical analysis, and, in any case, the results obtained were not much better than traditional methods that relied on the experience of the maintenance department and judgment of the utility management in selecting pipes for replacement. These studies primarily indicate that, once buried, the deterioration rate of pipe is not uniform, but is affected by a number of interdependent factors, and that the relationships among these various factors is apparently too complex to permit useful generalized description. The result is that there are no universally accepted criteria or quantitative rules for identifying which pipes in a system should be replaced at any given time. These facts greatly complicate the process of selecting pipes for replacement on any rational basis.

The City of Boulder provides an average of 21 million-gallons per day of treated water to over 108,000 customers. Water is treated at the City's two water treatment plants and delivered to customers via more than 420-miles of distribution pipelines. In general, pipes tend to deteriorate with age and replacement is an essential part of maintaining the City's basic infrastructure. To maintain the integrity of the water distribution system, the City budgets annually for replacement of pipes considered to be in the worst condition. However, only a small fraction of the system is replaced each year resulting in a progressive aging of the system.

Historically, Boulder's annual pipe replacement projects have been developed to replace apparent problem pipes based mainly on maintenance records. Decisions were made with limited data regarding the potential condition of individual pipes and with essentially no basis for assessing the probability of future break occurrences. It was also difficult to define the limits of pipe replacement projects so that deteriorated sections are replaced without replacing pipe that is still in serviceable condition. The objective of this study was to establish a more effective basis for defining pipe replacement projects by developing a systematic process for selecting pipes for replacement based on pipe condition and potential for future problems. Given that no universal rules exist for selecting pipes for replacement, this study sought to determine unique cause-of-failure relationships for the City of Boulder's water distribution system by analyzing the data available for the City's system. These results were then used to develop an evaluation process that, when applied, would identify pipe segments with the highest priority for replacement.

System Characteristics

To identify cause-of-failure relationships unique to the City of Boulder's water distribution system it was necessary to develop an in-depth profile of the characteristics of the system. Information for this purpose was derived from data furnished by the City from its Geographical Information System (GIS). Files included databases, and drawing overlays describing existing facilities along with data on water main breaks for the 11-year period from 1990 through 2000. A soil-type overlay derived from U.S. Department of Agriculture Natural Resources Conservation Service (formerly Soil Conservation Service) data was also used.

An initial review of the break data indicated a total of 904 breaks in the eleven-year inventory. This is an average of 82 breaks per year, about 1.6 per week. From 1990 to 1998 the annual average number of breaks ranged from 63 to 90. In 1999, 93 breaks were reported and in 2000 there were 121. However, no clear trend of increased frequency of failure with age was apparent. To investigate the possibility of relationships among various factors the data were further analyzed using two basic techniques:

1. Overlaying various combinations of characteristics on maps of the distribution system to help identify key parameters for judging pipe

condition by showing their distributions across the system and the degree of correlation among parameters.

2. Manipulating the databases to identify various common factors and relative relationships.

Map Overlays

The first data analysis operation plotted the locations of all of the reported breaks for the 11-year data period on a map of the distribution system. This map indicated visually that break occurrence is not uniformly distributed across the service area but that certain areas have higher densities than others. Additional overlays were created to identify possible factors related to this uneven distribution.

City water pipe data was sorted by age into ten-year blocks back to 1950. Pipes installed prior to 1950 are identifiable only as older than 50 years. The average age for pipe in the system was estimated to be 34 years with all pipes dated as prior to 1950 given an age of 50 years. When the pipe break locations were laid over the pipelines identified by age, no clear indication of correlation with pipe age alone is observed.

Similar overlays were made for pipe materials, pipe sizes, and break causes and various combinations of factors. Again, no strong correlations were visually apparent. However, when soil types were superimposed on a map of the system a strong visual correlation could be seen. For example, pipes located within the historical flood plain of Boulder Creek through central Boulder are in gravelly alluvium referred to as Niwot soils and appeared to have relatively few breaks. By contrast, a soil type referred to as Longmont clay, described as salty or alkaline, covers a significant portion of the Gunbarrel area where break frequency is high. Consideration of the observations presented by these various maps suggested where further data analysis should focus.

Data Analysis

Database analysis proceeded following the several directions suggested by the map overlay evaluation.

Pipe Age. Because pipe age is considered to be such an obvious factor in the deterioration of pipe, the lack of correlation presented by the visual analysis was tested by further analyzing the available data. The City's most recent Treated Water Master Plan, adopted in December 2000, established an average age of 34 years for the distribution system, with a significant portion of the pipes more than 50 years old, and some dating to the late 1800s. However, the break record database did not contain data on the age of pipes that had failed. Consequently, the break record database was refined by adding pipe age data, which allowed the age of the pipe to be established for each break event. As shown on Figure 1, the data indicated a general trend of increasing frequency of breaks as pipes aged but the correlation is neither strong nor uniform.

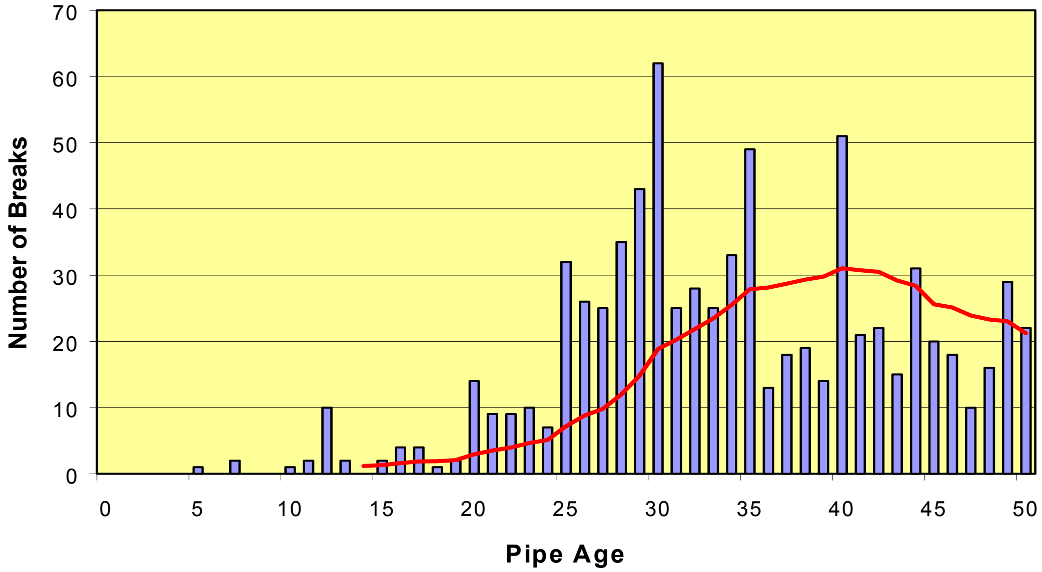

Figure 1
Distribution of Breaks by Age of Pipe

Other factors such as soil type and installation conditions appear to have a greater influence on the integrity of a pipeline. When the break age data was normalized in proportion to the fraction of the system pipes in each age bracket the general pattern evident in the chart was confirmed. The results, summarized in Table 1, indicate that up to an age of about 20 years pipe breakage is infrequent. After the 25-year point the break frequency rises dramatically and remains relatively constant from then on. The apparent drop-off after 40 years may be due more to inaccurate records for installation dates than to an actual drop in break frequency for the oldest pipes.

Table 1 Pipe Break Distribution by Age of Pipe

Pipe Age Range	Percent of System Pipes	Percent of Breaks
0-10 years	10	1
11-20 years	1	5
21-30 years	7	33
31-40 years	50	35
41-50 years	16	23
> 50 years	16	3

Pipe Material. Data on pipe material was evaluated to identify possible correlation with break frequency. As shown in Table 2, this analysis indicated that pipes constructed of cast iron have a disproportionate number of breaks relative to the fraction of the system they make up. Ductile iron pipes have a much lower break frequency and polyvinyl chloride pipes have very low break frequency in relation to the fractions of the system they make up. Asbestos cement and steel pipes have break frequencies relatively proportional to the fractions of the system they comprise.

Table 2 Pipe Break Distribution by Pipe Material

Pipe Material	Percent of System Pipes	Percent of Breaks
Cast Iron	40	65
Ductile Iron	30	18
Polyvinyl chloride	15	1
Asbestos Cement	4	2.5
Steel	4	2.5

Pipe Size. Data on pipe size was evaluated in the same way as the pipe material data. The results, summarized in Table 3, suggest a correlation that may be somewhat age related. Pipe age analysis indicates that the average age for 4-inch pipe is 41 years, 40 years for 6-inch pipe, but only 29 years for 8-inch pipe. The average age for pipes sized between 12-inch and 30-inch is 31 years.

Table 3 Pipe Break Distribution by Size of Pipe

Pipe Size	Percent of System Pipes	Percent of Breaks
4-inch	4	12
6-inch	25	40
8-inch	40	26
12-inch	15	6
12 to 30-inch	15	5
> 30-inch	< 2	0

Pressure. Pressure is reported as the cause for about 12 percent of breaks. Plotting the locations of the pressure breaks on a map of the system did not show a defined distribution pattern or correlation to known or modeled high pressure areas. Pressure surges are known to occur within the system and may be a major cause of breaks identified as due to corrosion as well as those attributed to pressure. However, the available data do not allow the correlation of pressure surges and breaks.

Break Causes. Break records indicate settlement causes 43 percent of breaks, corrosion 31 percent, and pressure 12 percent. Other causes are attributed to 14 percent of breaks. The break record was also analyzed to identify any trends in break causes that could be meaningful. For example, in increase in failures attributable to corrosion might indicate that progressive deterioration was occurring that could result in a large amount of pipe needing to be replaced all at once. This is potentially one of the most significant factors to be evaluated since development of such a condition would probably necessitate large rate increases to correct. However, the available data, summarized in Table 4, do not indicate any significant trends either within a particular type of failure or a shift in dominance among types. The percentage of total failures attributable to corrosion declined from the low 40s in the early 90s to the low 30s in 2000. Over the same period, settlement failures increased slightly from the high 30s to the mid 40s while pressure failures remained relatively constant at 10 to 12 percent and failures due to other causes held to a range of 12 to 15 percent.

Table 4 – Break Causes by Year

Year	Corrosion	Pressure	Settlement	Other	Total
1990	37	9	33	11	90
1991	28	6	24	5	63
1992	31	7	35	12	85
1993	26	5	26	14	71
1994	22	14	36	16	88
1995	20	12	36	10	78
1996	16	11	42	7	76
1997	18	14	31	7	70
1998	12	6	44	7	69
1999	30	13	31	19	93
2000	37	13	54	17	121

Soil Type. The USDA Natural Resources Conservation Service soil map was used to study the association between soil type and break occurrence. Initial visual inspection of the distribution of breaks overlain on a map of soil types indicated some correlation between soil type and break frequency. To verify this apparent correlation, soil type was added to the breaks database The resultant distribution of break frequency relative to soil type is summarized in Table 5.

Table 5 Pipe Break Distribution by Soil Type

Soil Type	Percent of System Pipes	Percent of Breaks
NdD-Nederland very cobbly sandy loam, 1-12 % slopes	30.1	31.1
Nh-Niwot Soils	14.3	7.0
VaB-Valmont clay loam, 1-3 % slopes	12.1	7.9
NuB-Nunn clay loam, 1-3 % slopes	10.3	12.2
Te-Terrace Escarpment	9.0	15.4
Cu-Colluvial Land	4.2	4.5
Lv-Loveland Soils	3.9	2.3
NuC-Nunn clay loam, 3-5 % slopes	3.7	6.1
LoB-Longmont Clay, 0-3 % slopes	2.5	5.1
VcC-Valmont cobbly clay loam, 1-5 % slopes	1.8	1.2
HeC-Heldt clay, 3-5 % slopes	1.2	<1
Unidentified	1.2	<1

These data clearly show a definite correlation between soil type and break frequency. Pipes buried in Longmont clay loam have a break frequency twice as high as the fraction of the system these pipes comprise while pipes buried in Niwot soils fail only half as frequently as the fraction of the system they make up. The normalized results for the entire system are presented in Table 6.

Table 6 Pipe Break Distribution by Soil Type

Soil Type	Break Distribution
NdD-Nederland very cobbly sandy loam, 1-12 % slopes	1.00
Nh-Niwot Soils	0.49
VaB-Valmont clay loam, 1-3 % slopes	0.65
NuB-Nunn clay loam, 1-3 % slopes	1.18
Te-Terrace Escarpment	1.71
Cu-Colluvial Land	1.07
Lv-Loveland Soils	0.59
NuC-Nunn clay loam, 3-5 % slopes	1.64
LoB-Longmont Clay, 0-3 % slopes	2.03
VcC-Valmont cobbly clay loam, 1-5 % slopes	0.66
HeC-Heldt clay, 3-5 % slopes	0.36
Unidentified	0.09

Location. Visual observation of the distribution of breaks across the system indicated that the certain areas have disproportionate numbers of breaks. The City's quarter section grid system was used to more precisely identify areas across the system with high break occurrence rates. The relative break frequency for each grid square was established by determining the total number of breaks reported in a particular square for the eleven-year data period and dividing by the length of pipe within the square in thousands of feet. The average for the system was found to be about 0.25 breaks per 1,000 feet of pipe, with a range from zero to 0.8 breaks per 1,000 feet of pipe.

Evaluation System

The analysis of the available data indicated several factors that may be applied to establish the replacement priority of each pipeline segment in the City of Boulder's distribution system. A system for ranking pipes by their potential for breaking in the future was established by assigning points for each factor identified as having an influence on the life expectancy of buried pipe to each pipe segment listed in the database. The resultant point total for each pipe segment provides a relative ranking that translates into the replacement priority for a given segment; the higher the points the higher the priority for replacement. Once points were assigned for each pipe segment in the database, sorting by points total created a prioritized list. Selection of the criteria used in the sort determined the relative importance of the various factors in the prioritization. The prioritized list was then used to define themes in ArcView. Used together, the prioritized list and computer generated map overlays can be used to define projects for implementation. The following paragraphs explain the rationale for assigning points.

Break History

A pipeline break is a strong indicator of potential future problems. Although a single break could be due to an isolated cause that is eliminated when the break is fixed, more often the occurrence of a break indicates one or more conditions such as corrosion or poor installation that may contribute to repeat breaks. This tendency is illustrated by the many pipe segments in the breaks database with more than one reported break occurrence. Consequently, break history was given a relatively heavy weighting as a predictive factor. The breaks database was used to identify those pipe segments with reported breaks and the accumulated number of breaks for each segment over the eleven-year data period. Ten points were assigned for each reported break. Pipes that the breaks database indicated had been replaced had their break points reset to zero.

Pipe Age

The analysis of available data showed a definite trend of increasing frequency of pipe failure as pipes become older. However, the data did not indicate a progressively worsening rate of failure with time. Up to 20 years the failure rate is low and there is no apparent correlation between aging and break rates. After 25 years, the failure rate increases rapidly until an age of about 35 years, after which time the failure rate appears to stop increasing. Beyond 40 years the data actually indicate a declining trend in failure rate, although this may be due to inaccuracies in the pipe age records than to a real decrease in the pipe break rate. Because the available data do not clearly show progressive deterioration of pipes with age, points were assigned on the basis of age according to the following scale which accommodates the pipe age relationship to break frequency shown by the break data along with the general desirability of replacing the oldest pipes in the system regardless of any other factors.

Pipe Age:	> 50 years:	15 points
	25 – 50 years	10 points
	20 – 25 years	5 points
	< 20 years	0 points

Break Cause

Data on the causes of breaks show that settlement typically dominates followed by corrosion, pressure, and other factors. Certain correlations may appear evident. For example, metallic pipes built in Longmont clay show high rates of failure attributed to corrosion. However, no trends toward increasing frequency of a particular break cause were evident from reviewing the available data. This indicates that progressive deterioration that could result in a large number of pipes failing all at once due, say, to corrosion, is not occurring. Therefor, although it may be possible to correlate break type to some other criterion such as soil type, the additional refinement to the evaluation system relative to the required level of effort would be small. Consequently, no points were assigned for break cause.

Pipe Material

Data analysis indicates that pipes made of cast iron have a failure rate significantly higher than the fraction of the system they make up. Ductile iron pipes have a much lower relative failure rate but still account for a significantly higher percentage of breaks than the other pipe materials. Based on this analysis, points were assigned for pipe material according to the following scale:

Pipe Material:	CIP	10 points
	DIP	5 points
	PVC	0 points
	Steel	0 points
	ACP	0 points

Pipe Size

Owing to the disproportionate number of breaks and the desirability of eliminating pipe less than 6-inch size from the system, pipes of 4-inch size were given the highest replacement priority in this category. Six-inch pipes were also given a high priority rating based on the disproportionate number of breaks. Eight-inch pipes do not fail disproportionately often, but the failure rate is significantly higher than for pipes 12-inch and larger. Consequently, 8-inch pipe was given a priority lower than 6-inch pipe but higher than the lowest priority of 12-inch and larger pipe based on size alone. Points were assigned for pipe size according to the following scale:

Pipe Size:	4-inch	20 points
	6-inch	10 points
	8-inch	5 points
	> 8-inch	0 points

Soil Type

The type of soil in which a pipe is constructed appears to be a significant indicator of the potential for failure. Analysis of the data indicated that of the eleven soil types occurring across the Boulder service area, four had disproportionately high break rates relative to the amount of installed pipe. Points were assigned to individual pipe segments based on the soil type according to the following scale:

Soil Type	Relative Break Frequency	Points
LoB-Longmont Clay	2.03	20
Te-Terrace Escarpments	1.71	10
NuC-Nunn Clay Loam (3-5percent slope)	1.64	10
NuC-Nunn Clay Loam (1-3percent slope)	1.18	5
All Others	< 1.0	0

Location

During the course of this study it was apparent that certain areas within the system that have higher than average break frequencies that are not attributable to the other criteria identified as factors contributing to reduced pipe life. The break rates may be due to various combinations of factors that are not evident from analysis of the existing data. For example, substandard installation may account for many failures in an area that was developed rapidly, a condition not readily identified by review of the system data. While an extensive data analysis could possibly clarify such complex relationships, identification of general areas having above average break rates provides a simpler method for attaining similar results. Thus, location of a pipe segment within the system becomes another criterion that can be applied in lieu of other more detailed factors to predict the potential for future pipe failures. Comparison of the normalized break rates in the individual grid squares to the system average resulted in assignment of points to individual pipe segments based on their location according to the following scale:

Relative Break Frequency:	< 1.1	0 points
	1.1 to 1.5	5 points
	1.5 to 2.0	10 points
	> 2.0	15 points

Applying the Evaluation System

The City's Waterpipe database was modified by removing all fields that do not directly relate to the evaluation process. Points were then assigned according to the scales described above. The database was then sorted based on three criteria:

1. Break Points
2. Total Points
3. Soil Type.

This operation resulted in a listing of every pipe segment in the distribution system ranked according to the points system derived from analyzing the break history data with a prioritization weighted first by past break history, second by total indicated points, and third by soil type. This weighting was chosen to keep the break history factor for pipes with one or two reported breaks from being overridden by the accumulated points for other factors.

The sorted list could be used by itself to define pipe replacements for budgeting purposes. However, joining the prioritized pipeline listing with the mapping capabilities of ArcView provides an additional level of refinement. When the 100 pipes with the highest priorities are highlighted on a map of the system, pipes that are physically related but have different rankings can be seen and logical project limits can be identified. Also, those cases where the break locations indicate that a pipe warrants replacement, but, due to the way that pipes are segmented in the database, the points totals for the individual segments do not result in a high priority ranking can be identified visually. Visual observation also facilitates application of objective criteria such as the criticality of a specific pipe to public safety or the potential for physical damage to property that could result from a break. These criteria are difficult to quantify in a database but will be apparent to someone familiar with the distribution system.

Effective application of the evaluation system will require the database to be kept current with regard to new pipe break information. Working with an up-to-date database, producing a system evaluation is a four-step process:

1. Sort the database to produce a “first cut” list of the highest priority pipes.
2. Select the top 100 or so pipes from this list and display them on the system map for visual analysis.
3. Visually analyze the displayed highest priority pipes and consider various objective criteria and apparent break patterns to adjust priorities.
4. Define projects based on final priorities and logical groupings of pipes to fit budget constraints.

Over the long term, it will also be necessary to periodically review the points assignments and selected sorting factors to accommodate changes in the condition of the system and new data as it becomes available.

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