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The role of leaks and breaks in water networks: technical and economical solutions

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ABSTRACT

This paper introduces a methodology that calculates the optimum replacement time for the pipes of a water network. This is done through a technico-economic analysis that takes into account all kinds of costs for the repair or replacement of trouble-causing parts of a network. The applied methodology uses the present value method of economic analysis and suggests alternative ways to specify the models of break rates for the various kinds of pipes. This goal becomes possible using the proven strong relationship between the leaks and breaks that occur in water pipes. Finally, the methodology presents a way of calculating the optimum replacement time for the pipes of a water network, by taking into account the water flow velocities (standard values and variations) in the pipes.

Key words | breaks, economic calculation method, leaks, repairs, replacements, water networks

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INTRODUCTION

Several studies and field experience in water networks have proved that the water volumes being lost due to leaks and breaks through transfer and delivery are significant proportions of the total water volume supplied. In Europe and the USA, according to the latest directives, the water losses that occur in a network should not exceed 15% and 10% of the total water supply, respectively. In Greece, studies reveal that these water losses are nearly 30% and sometimes even exceed 50%, in big and small cities, respectively. One-third of the losses is from the water supply system and the remaining two-thirds the water delivery system. It has also been found that, over the years, the mean water volume lost due to leaks is twice to five times greater than the water volume lost due to breaks. This increased importance of leaks results from the fact that they are more difficult to detect than the breaks and has to do with the various parameters connected to the characteristics or the control level of the network. Recent studies in newly installed nets showed that the starting number and rates of break incidents are minor compared to those of leaks, due to poor installation (Goulter & Kazemi 1988).

OPTIMUM REPLACEMENT TIME FOR THE PIPES OF A WATER NETWORK

The first step to determine the optimum replacement time for a single pipe or a section of a network is to develop, through regression, a mathematical model forecasting its future breaks. The success of this attempt mostly depends on the quality of the data records including all the necessary details related to the pipe-breaks that have already occurred. Unfortunately, these data records are usually inadequate, due to various operational problems of the Water Utility department responsible for collecting and keeping them. This fact results in poor, or even worse, a complete lack of pipe-break recording. This occasional recording of breaks is justified from the water utility's point of view, because leaks are responsible for the loss of 15% of the total water volume supplied by the treatment plants into a water network, when at the same time breaks are to blame for only 3% of the losses (Figure 1) (Kanakoudis 1998). It is common for the water utility to keep uninterrupted detailed leak records in pipe bodies, joints, connections and valves rather than break records.

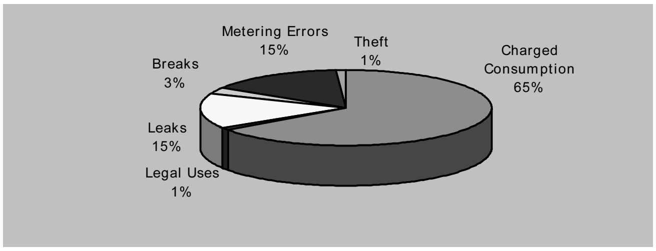

Figure 1 | Allocation of the water volume entering the CWSS system.

In the present work an alternative way to overcome the problem of poor break records is being presented, by investigating the probable correlation between the records of leaks and breaks, based on the fact that both failures are being affected, more or less, by the same parameters. This investigation includes five consecutive stages. In the first stage, the annual data records of breaks and leaks are categorized according to the material (e.g. amiantus, cast-iron, steel, PVC) and the size (mains, delivery) of the pipe. In the second stage, the correlation between these data records is checked, presupposing that both are timely comparable, based on their total common 'life', or separately on every single year. In this second situation special importance is given to the parameters that affect the emergence of break and leak incidents, whose values keep changing with time. The importance of these parameters wanes when the correlation check between the data records is based on their total common 'life'. As far as the yearly correlation check is concerned, this can refer to the whole year or separately to every single month. Although the second approach seems to be more accurate, it can lead to the wrong conclusions mainly due to doubts concerning the exact time of recording an incident at the beginning or the end of each month. During the third stage, the correlation (r) and determination (r^2) coefficients are evaluated in order to develop, through regression analysis, the mathematical law—linear or exponential—that best approaches the relations between the data records of breaks and leaks. The acceptable levels for these field data-derived coefficients are greater or equal to 0.85 and 0.75, respectively. In the fourth stage, the process of completing the breaks data records, using the appropriate mathematical law, takes place. When the leaks data record does not include discrimination according to the material of the pipe, then the categorization is limited to the pipe's use and size, and the same technique is followed. Finally, in the fifth stage, categorization of the complete breaks data records according to the pipe material, use and size takes place, assuming that the allocations of leaks and breaks, according to the material of the pipe, are being ruled by the same basic principles. When the leaks data record does not include discrimination according to the pipe material, then the categorization is limited to the pipe's use and size, and the same technique is followed (Kanakoudis 1998; Kanakoudis & Tolikas 2000).

Break rate forecasting models

The first attempts to develop models forecasting pipe break rates by statistically processing data from previous failures, took place in the late 1970s. This was also the time when the study of the several parameters affecting the characteristics of a pipe break was initiated (Lane & Buehring 1978). The first results showed that the break rates were not as strongly related to the age of pipe as it was initially supposed (O'Day 1982). This discovery was contradicted by a sequence of more detailed scientific studies, with regard to the break databases used to confirm the initial doubt (Kettler & Goulter 1985). These studies also revealed a strong correlation between the size of the pipe and the type and rate of the breaks that this pipe experiences. Specifically, in delivery pipes (pipe diameter <400 mm) beam breaks (circumferential) occurred due to the pipe's static attitude. In contrast, in mains (pipe diameter >400 mm) ring breaks (longitudinal), crushing-hole blowout and joint failures occurred. In specific environmental conditions the break rates of delivery pipes are higher than those of the mains. Doubt was cast on this discovery by the results presented by Walski and Pelliccia in 1982. In the same year in his study, Clark successfully combined the pipe break rates with the size, the pressure conditions, the exterior loads and the neighbouring conditions of the pipe. Also in 1985, Kettler and Goulter examined the break rates variations in conjunction with the pipe's material and analysed the types of breaks for various pipe material. In the late 1980s, Goulter and Kazemi, in successive attempts, proved the time and space clustering of breaks near an initial failure using the data available for the city of Winnipeg, Canada. The applied methodology is based on previous studies (Shamir & Howard 1979; Clark & Stevie 1981; Clark & Goodrich 1989; Cabrera *et al*. 1995). Walski and Pelliccia (1982) showed that the exponential mathematical model best approaches the relation between the data records of breaks and leaks that occur in delivery pipes, considering the time (t) since their installation. Throughout the model's determination process, the exact installation time (t_0) is required, or alternatively the mean installation time for each kind of pipe (material, use, size) (Kanakoudis 1998; Kanakoudis & Tolikas 2000).

Analysis of the various costs related to a pipe's break

The *replacement cost* of a pipe includes general expenses and abnormal costs and is determined by considering the material, dimensions (length and size) and position (road or pavement) of the pipe, using analytical tables. The *repair cost* of a pipe depends on the characteristics of the break (magnitude and significance) and the method followed for the repair. The total repair cost includes: (i) costs directly related to the repair works (labour, transport, equipment, repairing materials, landscaping, supervision, general and abnormal costs), and (ii) costs that quantify the effects of the break concerning the customers of the water service and the service itself. The reasons for these costs are as follows:

- The service's water intake, treatment and supply expenses concerning the water losses during the breaks are not reciprocal
- During the repairs, the service fails to satisfy the water needs (pressure and volume), resulting in missing revenues
- Fire extinguishing water supplied pressure falls
- Damages to a third party during repair works
- The annoyance and dissatisfaction of the public as a result of the repair works (social cost)

This cost can be two (small delivery pipes) to four (main supply pipes) times the actual cost of the repair work itself.

Optimum replacement time of a pipe when the new pipe is break-free

The economical analysis takes place assuming that the age–break function of a pipe is the exponential:

$$N(t) = N(t_0) * e^{A(t-t_0)}, \tag{1}$$

where t is time in years, t_0 the time that the pipe was installed, $N(t)$ the number of breaks per km of the pipe in year t and A the growth rate coefficient (1 year^{-1}). Another assumption is that the analysis refers to a specific type of break, for which restoration time does not vary with time. These assumptions ensure that the length of the pipe involved during a break, the repair and the replacement costs do not vary with time, resulting in a constant repair unit cost UC_{Rr} (dr per repair). The repair cost of breaks in year t is:

$$C_{Rr}(t) = UC_{Rr} * N(t) = UC_{Rr} * N(t_0) * e^{A(t-t_0)}. \tag{2}$$

If t_p is the present year, then:

$$PV[C_{Rr}(t)] = \frac{C_{Rr}(t)}{(1+R)^{(t-t_p)}} = \frac{UC_{Rr} * N(t)}{(1+R)^{(t-t_p)}} = \frac{UC_{Rr} * N(t_0) * e^{A(t-t_0)}}{(1+R)^{(t-t_p)}} \tag{3}$$

where R is the mean annual rate of inflation. Considering that the replacement takes place in year t_r then the present value of total cost for the previous repairs $t_r - t_p$ is:

$$PV[\sum C_{Rr}(t)] = \sum_{t=t_p}^{t_r} \frac{C_{Rr}(t)}{(1+R)^{(t-t_p)}} = \sum_{t=t_p}^{t_r} \frac{UC_{Rr} * N(t_0) * e^{A(t-t_0)}}{(1+R)^{(t-t_p)}}. \tag{4}$$

The replacement cost has constant unit value UC_{Rm} (dr per km) and present value:

$$PV[C_{Rm}(t_r)] = \frac{UC_{Rm}}{(1+R)^{(t_r-t_p)}}. \tag{5}$$

Considering Equations 4 and 5 it is obvious that the present value of total repair cost increases with the increase of t_r as another term is added each year. The present value of the replacement cost decreases with the increase of t_r because its denominator decreases as its exponent increases. The present value of total maintenance cost is:

$$PV[C_{tot}(t_r)]=PV[\sum C_{Rr}(t_r)]+PV[C_{Rm}(t_r)]= \left[\sum_{t=t_p}^{t_r}\frac{UC_{Rr}*N(t_0)*e^{A(t-t_0)}}{(1+R)^{(t-t_p)}}\right]+\frac{UC_{Rm}}{(1+R)^{(t_r-t_p)}}. \quad (6)$$

The optimum replacement time t^*_r, which is obtained by differentiating Equation 6, setting equal to zero and solving for t_r is:

$$t^*_r=t_0+\frac{1}{A}*1\text{n}\left[\frac{UC_{Rm}*1\text{n}(1+R)}{UC_{Rr}*N(t_0)}\right] \quad (7)$$

which corresponds to the year in which the annual increase in repair cost is equal to the annual decrease in replacement cost.

Optimum replacement time of a pipe when the new pipe is of the same type

In this case the new pipe is expected to experience breaks that follow the rate of the existing pipe. In the replacement year the number of breaks in the old pipe is given by Equation 1 for $t=t^*_r$. Similarly, the number of breaks for the new pipe is given by the same equation for $t=t_0$ (time zero is the installation year of the new pipe). Equation 7 shows the first replacement of the new pipe will be in year t^*_r and from then every $t_c=t^*_r-t_0$ years. The length of the optimal replacement cycle t^*_c is:

$$t_c=t^*_r-t_0=\frac{1}{A}*1\text{n}\left[\frac{UC_{Rm}*1\text{n}(1+R)}{UC_{Rr}*N(t_0)}\right]. \quad (8)$$

If every cycle is studied separately and the total repair and replacement costs are expressed as present values at the beginning of the cycle, then each cycle is balanced in itself and the overall optimal timing for the first replacement t^{**}_r is:

$$t^{**}_r=t_0+\frac{1}{A}*\left[\frac{\{[UC_{Rm}+PV[\sum C_{Rr}(t^*_c)]]*B(t^*_c)+\text{UC}_{Rm}\}*[1\text{n}(1+R)]}{(1+R)^{(t_r-t_p)}}\right]. \quad (9)$$

Although this expression is similar to Equation 7, its second term contains the factor $[UC_{Rm}+PV[\Sigma C_{Rr}(t^*_c)]]*B(t^*_c)$, which accounts for the future cycles of replacement and repair. Therefore $t^{**}_r>t^*_r$.

Sensitivity analysis of the optimum replacement time

The sensitivity of t^*_r to variations in its parameter values (checking its rate of variation when changing one parameter at a time and keeping the other parameters at their typical values), is obtained by differentiating t^*_r with respect to each parameter. The equations expressing this sensitivity analysis are:

$$\left(\frac{t^*_r}{R}\right)'=\frac{1}{A*(1+R)*1\text{n}(1+R)},$$

$$\left(\frac{t^*_r}{A}\right)'=-\frac{1}{A^2}*1\text{n}\left[\frac{UC_{Rm}*1\text{n}(1+R)}{UC_{Rr}*N(t_0)}\right],$$

$$\left(\frac{t^*_r}{UC_{Rr}}\right)'=-\frac{1}{A*UC_{Rr}},$$

$$\left(\frac{t^*_r}{N(t_0)}\right)'=-\frac{1}{A*N(t_0)},$$

$$\left(\frac{t^*_r}{UC_{Rm}}\right)'=\frac{1}{A*UC_{Rm}}.$$

APPLICATION OF THE METHODOLOGY IN THE ATHENS WATER SYSTEM

In Athens, the delivery water network of 7,000 km total length satisfies the daily needs (1,000,000 m^3, a mean annual value) of its active population (4,000,000 people that live and/or work in Athens) and is run by Capital's Water and Sewerage Service (known as CWSS). The supply system transfers water from four treatment plants to the city where the delivery system, through 'supply'

Table 1 | Allocation of leaks considering the size of each section of the CWSS system

	Pipes		Rest of appliances		Customers connections		Total	
Leaks %	Total section	Total network	Total section	Total network	Total section	Total network	Total section	Total network
Athens	43.3	49.83	32.6	53.99	24.1	69.98	100.0	55.07
Piraeus	53.3	25.19	33.7	22.85	13.0	15.47	100.0	22.5
Heraklion	53.3	24.98	34.4	23.16	12.3	14.55	100.0	22.43
Total network	47.6	100.0	33.25	100.0	19.15	100.0	100.0	100.0

pipes (mains ≥Φ400 mm, 1,200 km total length) and 'delivery' pipes (small <Φ400 mm, 5,700 km total length), satisfies 1,600,000 customer connections. Of these connections 98.75% are for domestic and 1.25% for industrial uses. From a managerial point of view the delivery network of CWSS is divided into three sections, Athens, Piraeus and Heraklion, with total length of 2,150, 1,950 and 2,600 km, respectively. The pipes' materials are cast iron, steel, amiantus-concrete and PVC. The delivery pipes are made of all kinds of materials and the mains of cast iron and steel. In contrast to steel mains, the cast iron pipes are not lined (Kanakoudis 1998; Kanakoudis & Tolikas 2000).

Water losses

The main assumption for applying the suggested methodology is the existence of data records for leaks and breaks. CWSS has kept such records since 1989, from which it can be observed that the water losses in the delivery system are almost 35% of the total water volume leaving the water treatment plants (Figure 1).

Significance of the leaks

The leaks of the CWSS system are responsible for the loss of 15% of the total water volume daily supplied by the treatment plants. The data records of leaks were modified to computer files, for the needs of this particular study, using the Excel program, and then were properly processed using Access (Table 1). This process emphasized the importance of leaks in the bodies of the pipes as they amount to 47.6% of the total number of leaks occurring in the system.

Correlation between leaks and breaks (section of Athens)

The water losses due to leaks are five times those due to breaks and that is why CWSS's data records of breaks are so poor compared with those of leaks. The process of completing the records of breaks uses comparable files as far as their recording periods are concerned. At first the monthly correlation of the comparable records was estimated and proved to be poor as expected. This correlation is affected by the accurate recording of the failures, especially at the beginning and the end of every month. The correlation (r) and determination (r^2) coefficients were at the levels of 65% and 40% respectively, proving that there was a continuous error due to delay in recording the failures. The next attempt refers to annual correlation of the two kinds of data files, which primarily were classified concerning the dimensions of the pipe that failed. This attempt showed that r and r^2 were at the levels of 90% and 75% respectively, verifying the strong relation between leaks and breaks. The allocation of the complete data file of breaks according to the pipe's material was achieved assuming that it is close enough to those of leaks (Table 2).

Table 2 | Allocation of leaks and breaks according to the material and use of each pipe

	Cast iron 700 km (1945)	Cast iron <Φ400 mm 550 km	Cast iron >Φ400 mm 150 km	Steel 650 km (1975)	Steel <Φ400 mm 200 km	Steel >Φ400 mm 450 km	Amiantus 1000 km (1975)	Total network 2450 km
L./BR.(90)	122/850	119/836	3/14	12/76	6/50	6/26	36/247	170/1189
BR. (1990)	1.2142	1.52	0.0933	0.1169	0.250	0.058	0.247	0.4853
L./BR.(91)	105/929	102/914	3/15	17/78	8/51	9/26	29/248	151/1298
BR. (1991)	1.327	1.6618	0.1	0.12	0.255	0.06	0.248	0.5298
L./BR.(92)	70/691	67/675	3/16	7/79	2/52	5/27	25/249	104/1031
BR. (1992)	0.9871	1.2273	0.1067	0.118	0.26	0.06	0.249	0.4208
L./BR.(93)	62/760	61/743	1/17	9/81	2/54	7/27	12/250	83/1105
BR. (1993)	1.086	1.351	0.113	0.125	0.27	0.06	0.250	0.4510
L./BR.(94)	59/847	57/829	2/18	4/89	2/61	2/28	10/259	73/1205
BR. (1994)	1.21	1.507	0.12	0.131	0.305	0.062	0.259	0.4918
L./BR.(95)	73/783	69/656	4/26	7/91	5/63	2/28	26/261	106/1037
BR. (1995)	0.9743	1.1927	0.1733	0.14	0.315	0.062	0.261	0.4232

Models forecasting the rates of break events according to the pipe's material and use

From Table 2 it is possible to develop through regression analysis the mathematical models that forecast the break events according to the pipe's material. Pipes of the same material lasted 30 years, so for each material the weighted mean installation year t_0 of each type of pipe was used. Multiple checks verified that the exponential models forecast best the rates of break events (Table 3).

Basic conclusions

For the cast-iron pipes the values of A range between the limits recorded in Shamir and Howard (1979) and Walski and Pelliccia (1982). The lowest values of A refer to amiantus pipes and steel mains. The first are not amenable to corrosion, due to their material, but are amenable to erosion and failures during their installation. Steel mains do not face these problems, as they are lined. The highest values of A are for cast-iron pipes and steel delivery pipes. Both are amenable to corrosion and erosion due to their material. Mains experience higher break rates than the delivery pipes do, due to the greater velocities developed. The present study verified the abovementioned results only for the cast iron pipes (delivery and mains) as neither are lined.

Estimation of optimum replacement times and their sensitivity analysis

The optimum replacement time t^*_r, considering the maintenance and replacement costs of all types of pipe included in the Athens section, is estimated by applying Equation 7, which was the final result of the analysis. Table 4 presents the results of this process.

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Table 3 | Models forecasting the rates of breaks

Pipe material	Break rate $N(t)$ (breaks km^{-1}*day)	Correlation coefficient r	Determination coefficient r^2	Annual increase of breaks rates (%)
Amiantus $<\Phi$400 mm	$0.2155*\exp(0.01171*t)$	0.92	0.84	1.18
Cast-iron $<\Phi$400 mm	$0.02745*\exp(0.0892*t)$	0.94	0.88	9.33
Cast-iron $>\Phi$400 mm	$0.00076*\exp(0.1057*t)$	0.90	0.81	11.15
Steel $<\Phi$400 mm	$0.11565*\exp(0.04944*t)$	0.945	0.90	5.07
Steel $>\Phi$400 mm	$0.043*\exp(0.0191*t)$	0.925	0.85	1.93

The value of parameter R was determined using estimations from the Greek Ministry of Finance for the mean annual inflation rate. The values of the other parameters that affect t^*_r were determined as follows: (i) for the *replacement cost*, analytical tables of CWSS were used considering that all pipes are being replaced by new ones of the same material, apart from cast-iron mains and small pipes that are being replaced by steel and plastic pipes respectively; (ii) the actual *repair cost* of a typical break was estimated by analytical tables. The estimation of the 'social' part of this cost was based on the experience of CWSS's staff and verified by telephone research with customers. The results of this attempt to estimate the social cost related to the annoyance of the public during repair works, is summarized as follows:

For typical breaks that occur in small delivery pipes (or mains), the 'social' part of the repair cost is twice (or four times) the actual repair cost, that is $D=3$ (or $D=5$).

For mains the value of the repair cost multiplier D is greater than for small delivery pipes, due to the flexibility of the network which can quickly and easily overcome the break of a small pipe, as it operates in loops. In contrast a break on a main pipe results in disruption of the water delivery process usually for many hours. The last two lines of Table 4 present the values of $(t^*_r - t_0)$ for the various types of pipe with or without the affect of the social cost. Table 5 presents the results of the sensitivity analysis of t^*_r.

Basic conclusions

The cast-iron pipes were installed from 1930 to 1960, so the replacement of the small pipes should have started from 1999 (1930 + 69), and must be completed by 2029 (1960 + 69). The calculated optimum replacement times for the cast-iron pipes (69 years for the small pipes and 89.5 years for the mains) are almost equal to those presented in Shamir and Howard (1979) and Walski and Pelliccia (1982) (60 and 100 years respectively). The calculated optimum replacement time for small delivery steel pipes (100 years) is equal to that presented in Shamir and Howard (1979) and Walski and Pelliccia (1982). These values are decreased by 20% when the social part of the repair cost is considered. The replacement of the steel mains proved to be non-economical due to their anti-corrosion protection. The calculated optimum replacement time for the amiantus-concrete pipes is another reason (in addition to their low cost) for their expanded use. The results of the sensitivity analysis of t^*_r, showed that the coefficient A that expresses the annual increase of break events, affects the level of t^*_r more than any other parameter. Inflation rate has the smallest effect justifying the use of approximate values. Also the optimum replacement time decreases (or increases) by one year, while the unit replacement cost decreases (or increases) by A*100%. Similarly the optimum replacement time decreases (or increases) by one year, while the unit repair cost increases (or decreases) by A*100%.

Table 4 | Optimum replacement time

	Amiantus <Φ400 mm	**Steel** <Φ400 mm	**Steel** >Φ400 mm	**Cast-iron** <Φ400 mm	**Cast-iron** >Φ400 mm
t_0	1975	1975	1975	1945	1945
$N(t)$	$0.2155\exp[0.01171(t-t_0)]$	$0.11565\exp[0.04944(t-t_0)]$	$0.043\exp[0.0191(t-t_0)]$	$0.02745\exp[0.0191(t-t_0)]$	$0.00076\exp[0.1057(t-t_0)]$
$\alpha = N(t_0)$	0.2155	0.11565	0.043	0.02745	0.00076
$A\ \eta\ b$	0.01171	0.04944	0.0191	0.0892	0.1057
R	5%	5%	5%	5%	5%
UC_{Rm}	30,000,000	50,000,000	100,000,000	40,000,000	100,000,000
UC_{Rr}	150,000	150,000	500,000	150,000	500,000
$D{*}UC_{Rr}$	450,000	450,000	2,500,000	450,000	2,500,000
$t{*}_r - t_0$	325	100	284	69	89.5
$t{*}_r - t_0(D)$	232	78	200	57	74

Table 5 | Necessary change of the parameter values for one year increase of (t^*_r)

%	Amiantus <Φ400 mm	Steel <Φ400 mm	Steel >Φ400 mm	Cast-iron <Φ400 mm	Cast-iron >Φ400 mm
R	+ 1.20	+ 5.07	+ 1.96	+ 9.14	+ 10.83
$\alpha = N(t_0)$	– 1.17	– 4.94	– 1.91	– 8.92	– 10.57
$A\ \eta\ b$	– 0.61	– 1.19	– 0.53	– 1.64	– 1.12
UC_{Rm}	+ 1.17	+ 4.94	+ 1.91	+ 8.92	+ 10.57
UC_{Rr}	– 1.17	– 4.94	– 1.91	– 8.92	– 10.57

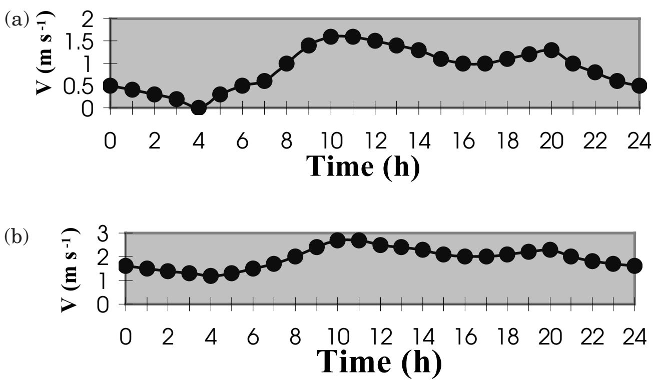

Figure 2 | Daily variations of velocity in small delivery pipes (a) and mains (b).

Considering the effect of velocity on the rates of break events

The records of CWSS (Kanakoudis 1998) show that small delivery pipes experience a mean flow velocity of 1 ms^{-1} between 16:00 and 24:00, with mean variations of: (i) -50% (0.5 ms^{-1}) during night hours between 00:00 and 08:00; and (ii) $+50\%$ (1.5 ms^{-1}) during peak hours between 08:00 and 16:00. For the mains the mean flow velocity is 2 ms^{-1} between 16:00 and 24:00, with mean variations of: (i) -25% (1.5 ms^{-1}) during night hours between 00:00 and 08:00; (ii) $+25\%$ (2.5 ms^{-1}) during peak hours between 08:00 and 16:00 (Figure 2).

These levels and variations of velocity are within the limits set for small industrial cities. The effect of velocity on break rates is quantified through the mathematical form:

if $Vi < Vmin$ or $> Vmax$ then $b' =$

$$b_0\left[1 + w\sum\left(\frac{|V_i - V_{ak}|}{V_{ak}}\frac{h_i}{24}\right)\right],$$

otherwise $b' = b_0$.

Where b' is the value of growth rate coefficient b_0 considering the effect of the velocity, is the value of growth rate coefficient b without considering the effect of the velocity, w is a non dimensional coefficient, $V_{\alpha k}$ the optimum velocity ($Vmin = 1.0$ ms^{-1}, $Vmax = 1.5$ ms^{-1}), v_i is the velocity that is not within the limits of the optimal velocities, and h_i is the time period during which the velocity has constant value equal to V_i. For the cast-iron pipes of CWSS the application of the previous equation results in:

1. Small delivery pipes: $0.08921 = b_o{*}[1 + (1.5/9){*}w]$ $=> w = 6{*}[(0.08921/b_o) - 1]$,
2. Mains: $0.1057 = b_o{*}[1 + (3.0/9){*}w]$ $=> w = 3{*}[(0.1057/b_o) - 1]$.

By solving the system presupposing that the intensity of the effect of velocity does not differ between small delivery pipes and mains gives: $b_o = 0.0727$ and $w = 1.362$.

CLOSING STATEMENTS: ECONOMIC ASPECTS

Using the results in Table 5 in conjunction with the application of the results of the previous paragraph, it is possible to quantify the negative effect to the pipes' optimum replacement time from the operation of the system in such a way that velocities are outside the optimal limits.

Specifically, the breaks that occur in small cast-iron delivery pipes increase at a mean annual rate of 9.33% ($e^{0.0892}$) and result in an optimum replacement time of 69 years after their initial installation. If the developing velocities were kept within the optimal limits then the breaks would have increased at a mean annual rate of 7.54% ($e^{0.0727}$) resulting in an optimum replacement time of 85 years. The increase of A by 22.7% from 0.0727 to 0.0892 decreased the optimum replacement time by 16 years (from 85 to 69 years). If the 'social' repair cost is considered, the decrease is 12.5 years (from 69.5 to 57 years).

The breaks that occur in cast-iron mains increase at a mean annual rate of 11.15% ($e^{0.1057}$) and result in an optimum replacement time of 89.5 years after their initial installation. If their developing velocities were kept within the optimal limits then the breaks would have increased at a mean annual rate of 7.54% ($e^{0.0727}$) resulting in an optimum replacement time of 130 years. The increase of A by 45.4% from 0.0727 to 0.1057 decreased the optimum replacement time by 40.5 years (130 to 89.5 years). If the 'social' repair cost is considered, the decrease is 34 years (108 to 74 years).

From the above results, in small delivery pipes 18.5% of the annual increase in break rates can be attributed to their developing velocities, while in the mains this reaches 31%.

Shortening the replacement times of the pipes by N years, the full economic damage that the water company experiences can be estimated through the following process:

The water company is being forced to spend the necessary amount of money (capital) to replace the pipes N years earlier than it could, resulting in capital interest losses over this extra time period, according to the equation: $C_{Interest-Loss} = C_{Rm} * [(1+R)^N - 1]$. The reduction of the system's worth-economic life (the life time period during which continuous pipe repairing costs less than pipe replacement) T by N years results in capital losses, as the inital investment is not fully depreciated within the shortened life of the pipes, according to the equation:

$$C_{Capital-Loss} = C_{Rm} * \frac{N}{T}$$

Applying the above equations to the system of CWSS:

Small delivery pipes

Total length of pipes: 550 km
Mean unit replacement cost: 40,000,000 dr km^{-1}
Mean worth-economic life of the pipes: 77.25 years
Mean reduction of this worth-economic life: 14.25 years

$C_{Interest-Loss} = C_{Rm} * [(1+R)^N - 1] = 550 * 40{,}000{,}000 * [(1+0.05)^{14.25} - 1] = 22.1 * 10^9$

$C_{Capital-Loss} = C_{Rm} * \frac{N}{T} = 550 * 40{,}000{,}000 * \frac{14.25}{77.25} = 4.1 * 10^9$

⇨Economic damage to the water company (CWSS) due to early replacement: 26.2 billion dr

Mains

Total length of the pipes: 150 km
Mean unit replacement cost: 100,000,000 dr km^{-1}
Mean worth-economic life of the pipes: 119 years
Mean reduction of this worth-economic life: 37.25 years

$C_{Interest-Loss} = C_{Rm} * [(1+R)^N - 1] = 150 * 100{,}000{,}000 * [(1+0.05)^{37.25} - 1] = 77.4 * 10^9$

$C_{Capital-Loss} = C_{Rm} * \frac{N}{T} = 150 * 100{,}000{,}000 * \frac{37.25}{119} = 4.7 * 10^9$

⇨Economic damage to the water company (CWSS) due to early replacement: 82.1 billion dr

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