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Planning renewal of water mains while considering deterioration, economies of scale and adjacent infrastructure

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Abstract

The structural deterioration of water mains and their subsequent failure are affected by many factors, both static (e.g., pipe material, pipe size, age (vintage), soil type) and dynamic (e.g., climate, cathodic protection, pressure zone changes). This paper describes a non-homogeneous Poisson model developed for the analysis and forecast of breakage patterns in individual water mains, while considering both static and dynamic factors. Subsequently, these forecasted breakage patterns are used to schedule the renewal of water mains in an economically efficient manner, while considering the various associated costs, including economies of scale and scheduled works on adjacent infrastructure.

In this paper, his principles of the approach are described briefly and its application is demonstrated with the help of a case study.

1. Introduction

The statistical analysis of historical breakage patterns of water mains is a cost effective approach to discern their deterioration, where physical mechanisms that lead to their deterioration are often very complex and not well understood. Furthermore, enormous variability exists in all the factors that contribute to pipe deterioration, and the data required to model these physical mechanisms are rarely available and prohibitively costly to acquire.

Many models have been proposed to discern historical breakage patterns and forecast anticipated future breakage rates. Kleiner and Rajani, (2001) provided a comprehensive review of approaches and methods that had been developed. Since then, several more methods have been proposed, such as Park and Loganathan (2002), Mailhot *et al.* (2003), Dridi *et al.* (2005), Giustolisi *et al.* (2005), Watson *et al.* (2006), Boxall *et al.* (2007) and Le Gat (2007) to name but a few.

Kleiner and Rajani (2008) proposed an approach based on the assumption that breaks on an individual pipe occur as a non-homogeneous Poisson process (NHPP). NHPP has been suggested by others to model the same phenomenon (e.g., Constantine and Darroch, 1993; Røstum, 2000; Jarrett *et al*., 2003, among others). However, these considered only static factors (i.e., pipe-intrinsic), while the approach proposed Kleiner and Rajani (2008) allowed for the consideration of dynamic factors as well. The NHPP-based model, with time-dependent (dynamic) covariates was named I-WARP (Individual water Main Renewal Planner).

Given a forecast of anticipated future breaks, Nafi and Kleiner (2009) proposed a method for the optimal scheduling of individual pipes for replacement, while considering practical issues such as harmonizing pipe replacement with known scheduled roadwork and economies of scale. Although this method is not restricted to any planning horizon length, it is deemed most suitable for short to mid-term planning (say, 5 years) due to practical considerations such as municipal budgetary planning horizon, confidence (or rather lack thereof) in longer term forecasting of breakage rates in individual water mains and likelihood of unforeseeable changing conditions.

In this paper we provide a brief introduction of the NHPP-based deterioration model (I-WARP) and the renewal scheduling model and demonstrate their application using a case study.

2. Non homogeneous Poisson-based model

In I-WARP we assume that breaks at year *t* for an individual pipe *i* are Poisson arrivals with mean intensity (or mean rate of occurrence) $\lambda_{i,t}$. Therefore, the probability of observing $k_{i,t}$ breaks is given by:

$$P(k_{i,t}) = \frac{\lambda_{i,t}^{k_{i,t}} \cdot \exp(-\lambda_{i,t})}{k_{i,t}!} \tag{1}$$

where $\lambda_{i,t} = \exp[\alpha_o + \theta\tau(g_{i,t}) + \underline{\alpha}\,\underline{z}^i + \underline{\beta}\,\underline{p}^t + \underline{\gamma}\underline{q}^{i,t}]$

where α_o is a constant, $\tau(g_{i,t})$ is the age covariate, and θ is its coefficient, $g_{i,t}$ is the age of pipe *i* at year *t*; $\underline{\boldsymbol{z}}^{\boldsymbol{i}}$ is a row vector of pipe-dependent covariates (e.g., length, diameter, etc.) and $\underline{\boldsymbol{\alpha}}$ is a column vector of the corresponding coefficients; $\underline{\boldsymbol{p}}^{\boldsymbol{t}}$ is a row vector of time-dependent covariates (e.g., climate) and $\underline{\boldsymbol{\beta}}$ is a column vector of the corresponding coefficients; $\underline{\boldsymbol{q}}^{\boldsymbol{i,t}}$ is a row vector of both pipe-dependent and time-dependent covariates (e.g., number of known previous failures - *NOKPF*, cathodic protection) and $\underline{\boldsymbol{\gamma}}$ is a column vector of the corresponding coefficients. We call the function $\exp[\theta\tau(g_{i,t})]$ "ageing function" and therefore coefficient θ is called "ageing coefficient". Note that if $\tau(g_{i,t}) = g_{i,t}$ then the aging is exponential, i.e., λ is an exponential function of pipe age, whereas if $\tau(t) = log_e(g_{i,t})$ the aging function becomes a power function, i.e., λ becomes a power function of pipe age. Year *t* is taken relative to the first year for which breakage records are available. Coefficients are found by the maximum likelihood method.

Note that this formulation implies that each covariate affects the mean intensity independently, i.e., interdependencies between covariates are assumed non-existent, unless a specific covariate is constructed to explicitly consider such interdependency (e.g., a ratio or a product of two "independent" covariates).

3. Covariates

The selection of covariates is obviously limited by the amount and quality of available data. Further, subject to fundamental assumptions, most pipe-dependent covariates (e.g., pipe material, vintage, etc.) can be considered explicitly in the probabilistic model or implicitly by partitioning the data into homogeneous populations with respect to these covariates. Kleiner and Rajani (2008) discussed at some length the implications as well as the pros and cons of the two approaches for considering these covariates. In this paper, with one exception, we used the latter, i.e., we applied I-WARP to ‘homogeneous’ groups of pipes. The exception is the pipe length covariate, which is considered explicitly.

In the category of time-dependent covariates, three climate-related covariates are considered, namely freezing index (*FI*), cumulative rain deficit (*RDc*) and snapshot rain deficit (*RDs*). A detailed introduction and a rational for using these covariates are provided in Kleiner and Rajani (2004). *FI* is a surrogate for the severity of a winter, *RDc* is a surrogate for average annual soil moisture and *RDs* is a surrogate for locked-in winter soil moisture (appropriate for cold regions, where soil/backfill can freeze in the winter). Note that climate-related covariates can be used to train the model on observed historical breaks but not to forecast (unless one endeavours to forecast climate as well). The rational for using climate-related covariates is that “true” background ageing rate (in terms of increase in breakage intensity as a function of time) are more likely to emerge if external effects, such as climate, are considered in the training process.

In the pipe and time-dependent category two pipe-dependent and time-dependent covariates are considered, namely number of known previous failures (*NOKPF*) and a covariate related to hotspot cathodic protection (*HSCP*).

The dependency of pipe failure rate on the number of previous failures has been observed by others (e.g., Andreou *et al*., 1987; Rostum, 2000). Typically, covariates used have been break order, or number of breaks observed since installation. As the vast majority of water utilities do not have a complete breakage history of pipes since installation (left censored data), a more realistically available (if less rigorous) covariate of previously known number of failures was selected.

There are generally two types of cathodic protection (CP) for water mains, retrofit and hotspot (*HSCP*). While retrofit CP is the systematic installation of sacrificial anodes along the pipe (or in anode beds), *HSCP* is the opportunistic placement of a sacrificial anode every time a pipe is exposed for repair. Kleiner and Rajani (2008) described the manner with which the *HSCP* covariate is computed and considered. The model does allow for the consideration of retrofit CP, but details are yet to be published in a forthcoming AwwaRF report. The case study presented here includes no retrofitted pipes.

4. The economics of pipe replacement

The present value of the total cost associated with pipe *i*, which is replaced at year *t* is given by

$$C_{i,t}^{tot} = CR_{i,t}e^{-rt} + \sum_{j=1}^{t} k_{i,j}[(C_i^{rep} + C_i^{dir} + C_i^{wat})e^{-rj} + C_i^{indir} + C_i^{soc}] \qquad (2)$$

where $CR_{i,t}$ is the cost of replacing pipe *i* at year *t*, e^{-rt} is the exponential form of discounting, *r* is the discount rate, $k_{i,t}$ is the expected number of breaks in pipe *i* at year

t, C_i^{rep} the cost of failure repair, C_i^{dir} is the cost of expected direct damage (e.g., to adjacent infrastructure, basement flooding, road damage), C_i^{indir} is the cost of indirect damage (e.g., accelerated deterioration of roads, sewers, etc.), C_i^{wat} is the cost of loss water, and C_i^{soc} is the social cost (e.g., disruption, time loss, pollution, loss of business, etc.). Note that the indirect cost and social cost components of pipe failure are not discounted. Note further that for public projects such as water main works it is appropriate to use "social discount rate", which is significantly lower (typically 1% - 3%) than financial discount rate. Equation (2) also implies that the number of failure expected to occur on the new replacement pipe during the planning period T is negligible. This implication is justified for relatively short planning periods.

The literature reflects (e.g., Shamir and Howard, 1979; Kleiner et al. 1998) that equation (2) generally describes a convex present value cost function as illustrated in Figure 1. Herz (1999) agreed that the cost function is generally convex but observed that often it is very flat, especially in the inclining branch (the right side) of the curve, creating a "hammock" shaped function. The point of minimum cost of pipe i (t_i*) is the point at which the marginal (discounted) cumulative cost of failure rate, which is essentially the expected (discounted) cost of failure at year t_i* equals the marginal savings due to deferral of replacement.

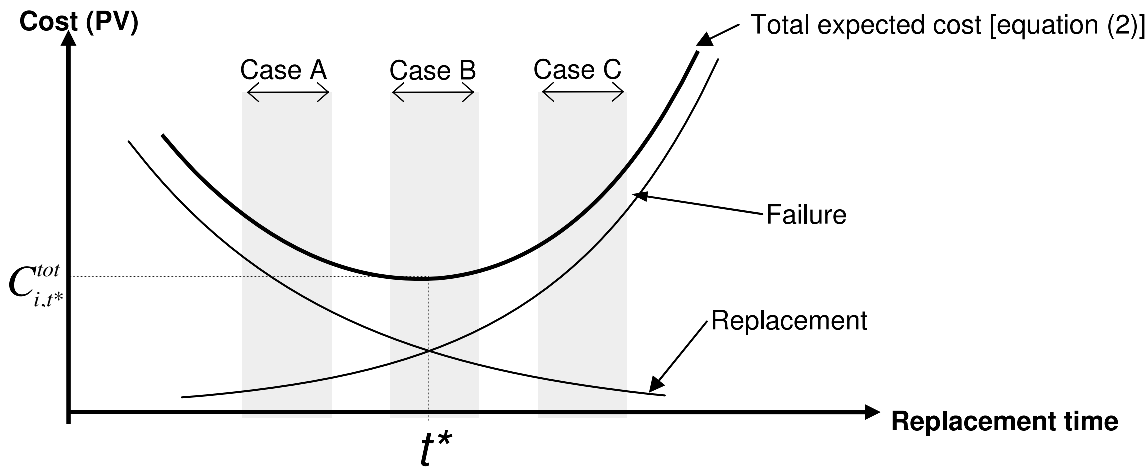

Figure 1. Costs associated with replacement timing

Based on the assumptions about the shape and properties of equation (2), the following three cases are understood for some planning period T:

1. T is located to the left of t_i* (i.e., case A in Figure 1)
2. T coincides with t_i* (i.e., case B in Figure 1).
3. T is located to right of t_i* (i.e., case C in Figure 1).

Barring any additional cost considerations, it is clear that in case 1, pipe i should not be replaced during T; in case 2, pipe i should be replaced at year t_i* and; in case 3, pipe i should be replaced at the first year in T. However, it could be cost effective to deviate from these clear rules in some situations due to economies of scale or timely coordination with scheduled replacement/renewal of adjacent infrastructure.

While cases 2 and 3 are straightforward, case 1 presents a dilemma, namely, how far into the future should one look to see if economies of scale or timely coordination with replacement/renewal of adjacent infrastructure works might warrant the advancement of a pipe replacement to period *T*. Clearly, the dimensionality of the problem becomes higher the farther into the future one has to look, . We determined that for a planning period of *T* years, a period of no more than 2*T*+1 years needs to be examined to ensure that no loss of feasible solution occurs.

Economies of scale

Pipe replacement cost was assumed to have two components, fixed and variable. The fixed component, *M*, is termed "mobilization component" and is taken as a lump sum, assumed to be approximately equal for all pipes in the inventory. The mobilization component comprises costs such as setting up the job site, signage, discovery and marking of adjacent infrastructure, etc. The variable component, Cr_i, is the length-unit cost ($/m) of replacing pipe *i* and it depends on pipe material, diameter, location and possibly other special circumstances (e.g., difficult access, rocky terrain, etc.). The cost of replacing pipe *i*, of length l_i is therefore

$$CR_i = M + Cr_i l_i \tag{3}$$

We observe two types of economies of scale: quantity discount, which applies to the variable component of pipe cost and contiguity discount, which applies to the mobilisation (fixed) component.

Figure 2 illustrates the concept for quantity discount: for a certain pipe material installed at a given year, unit cost discount is zero for a small quantity of pipes. When total quantity exceeds L^{min}, quantity discount starts kicking in and increases with pipe length to a maximum of D^{max}, which is obtained at quantities matching or exceeding L^{max}.

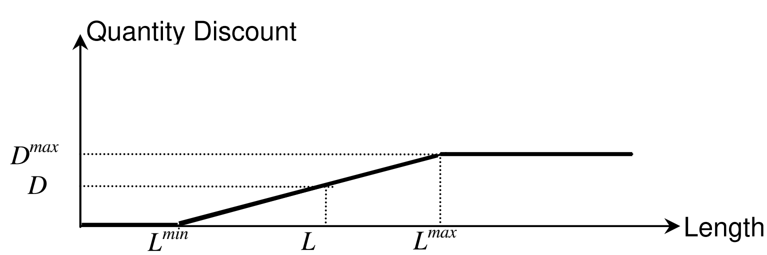

Figure 2. Quantity discount

Contiguity discount is defined as follows: if pipe *j* is contiguous to pipe *i* (both share the same node) and both are replaced in a given year *t* they are assumed to be part of the same replacement project and therefore only one mobilization component is levied. Therefore, if *k* contiguous pipes are replaced in a given year, their total replacement cost will comprise the sum of all their unit costs plus one mobilization charge (i.e., *k*-1 mobilisation charges were saved compared to the cost of replacing k non-contiguous pipes).

In addition, we also consider the benefit of possible coordination of pipe replacement with scheduled roadwork. It is assumed that the unit cost (variable component) of pipe replacement is discounted by p_i (e.g., \$/m or % of cost) if pipe i is replaced at the same year t that the pavement overlying it is scheduled for renewal. Equation (2) can now be modified to include all the savings described above:

$$\begin{aligned} C_{i,t}^{tot} &= CR_{i,t}e^{-rt} + \sum_{j=1}^{t} k_{i,j}[(C_i^{rep} + C_i^{dir} + C_i^{wat})e^{-rj} + C_i^{indir} + C_i^{soc}] \\ &\quad - (\textit{Mobilisation savings}_{i,t} + \textit{Quantity discount}_{i,t} + \\ &\qquad + \textit{Roadwork coordination savings}_{i,t})e^{-rt} \end{aligned} \tag{4}$$

The total pipe replacement budget for the entire planning horizon of T years is denoted by B. We consider two budget scenarios, namely annual budget and non-restricted global budget. In the annual budget scenario, B is divided into annual portions B_t and the total investment in pipe replacement in year t must not exceed B_t. The annual portions B_t can be equal portions, increasing/decreasing series or arbitrary. In the non-restricted scenario, B can be allocated to the planning period in the most economically efficient manner, where the only restriction is that the total pipe replacement costs in all years T cannot exceed B.

It is very important to note that for budgetary calculations pipe replacement costs (investments) are taken at their nominal values (including savings on economies of scale and timely coordination with scheduled roadwork renewal/replacement) and not at their present values.

5. Optimisation of replacement scheduling of pipes

The optimisation process has three major steps:

Step 1: Use I-WARP to produce a forecast of expected number of breaks for each pipe i in a homogeneous group of P pipes for each year t in the period of $2T+1$ years, where T is the planning period.

Step 2: For each pipe i in P compute $C_{i,t}^{tot}$ (equation 2) for each t in period $2T+1$. Pipes for which t^* (i.e., $C_{i,t}^{tot}$ is minimum) occurs at year $t = 2T+1$ are not considered for replacement in planning period T and are removed from the analysis pipe set. The subset of the remaining pipes for analysis is denoted by P'.

Step 3: Use multi-objective genetic algorithm (MOGA) to find a set of non-inferior feasible solutions, or policies (Pareto front). GANetXL (Bicik, 2008), a prototype non-commercial program (uses MS-Excel® as a platform) developed by the Centre for Water Systems (CWS) at the University of Exeter, UK was used in this study.

- The objectives for the MOGA are minimisation of total PV of costs (equation 2) and the maximisation of budget usage (minimisation of difference between available budget(s) and actual investment in pipe replacement). Note that budget and investment are considered at cash value while minimisation is done on the present value of costs.
- Imposition of budget constraint is achieved by penalising budget exceedance.
- Quantity discounts and contiguity discounts have to be recalculated for each candidate solution (policy).
- A policy may comprise pipes scheduled for replacement in year $t \leq T$ as well as pipes scheduled for replacement at year $t > T$. Within this policy only the former pipes are to be replaced within the planning period T. The latter are considered as pipes whose replacement is postponed to the next planning period.

6. Case study

We used a data set obtained from a water utility in Eastern Ontario, Canada. The utility has documented breakage records since 1972. The utility embarked on a hotspot cathodic protection program in 1984. For the analysis, 2 homogeneous groups of pipes were extracted. Group 1 comprised 6" (150 mm) diameter unlined cast iron (UCI) pipes installed in the 15-year period 1946-60, in total 391 individual pipe records (we respected the utility's definition of 'individual pipe' as was reflected in the database) with total length of about 54 km. Group 2 comprised 99 individual records of 8" (200 mm) diameter pipes of the same material and vintage, with total length of about 12 km. Pipes in both groups together formed a contiguous network (Figure 3). Climate data for the analysis years were obtained from Environment Canada.

6.1 Model training

I-WARP was applied to breaks recorded between 1972-2006 (training period). An examination of the coefficients (Table 1) reveals that background ageing is drastically different between the two groups. The length covariate in this case study was taken as the log_e of pipe length. This means that in Group 1 the influencing factor is pipe length to the power of approximately 2/3, while in Group 2 the power is greater than unity. The positive sign of *PKNOF* in Group 1 may point to a "worse than old" condition (in repairable systems three repair-related conditions are observed, "good as new", "good as old" and "worse than old"). However, in Group 2, *PKNOF* was statistically insignificant (at 5% significance level, using likelihood ratio test). The impact of climate covariates on the model was statistically insignificant in Group 2 and somewhat inconsistent in Group 1, where freezing index (*FI*) showed little impact, snapshot rain deficit (*RDs*) appeared to have a more pronounced impact, and cumulative rain deficit (*RDc*) showed a relative larger impact but in a counter intuitive direction (negative coefficient). Water mains at this water utility are typically buried at a depth of 2.4 m, which may explain the low impact of *FI*, but not the negative sign of *RDc*. The positive coefficient of *HSCP* in Group 1 is also contrary to expectation, as it reflects that hotspot anodes act to increase (instead of reduce) breakage intensity.

Table 1. Coefficients obtained from model training using I-WARP

	Group constant	*Ageing*	*FI*	*RDc*	*RDs*	*Length*	*PKNOF*	*HSCP*
Group 1	-8.47	0.48	0.07	-0.41	0.34	0.65	0.76	0.43
Group 2	-11.97	0.74	N/S*	N/S*	N/S*	1.14	N/S*	N/S*

*Statistically not significant at 5% level, using likelihood ratio test.

Figure 3 illustrates observed, and modeled number of breaks (aggregated by year) in the training period as well as the forecasted number of breaks for the two groups. Note that in Group 2, the modeled number of breaks is a rather smooth line because all time-dependent covariates were statistically insignificant and therefore removed from the analysis.

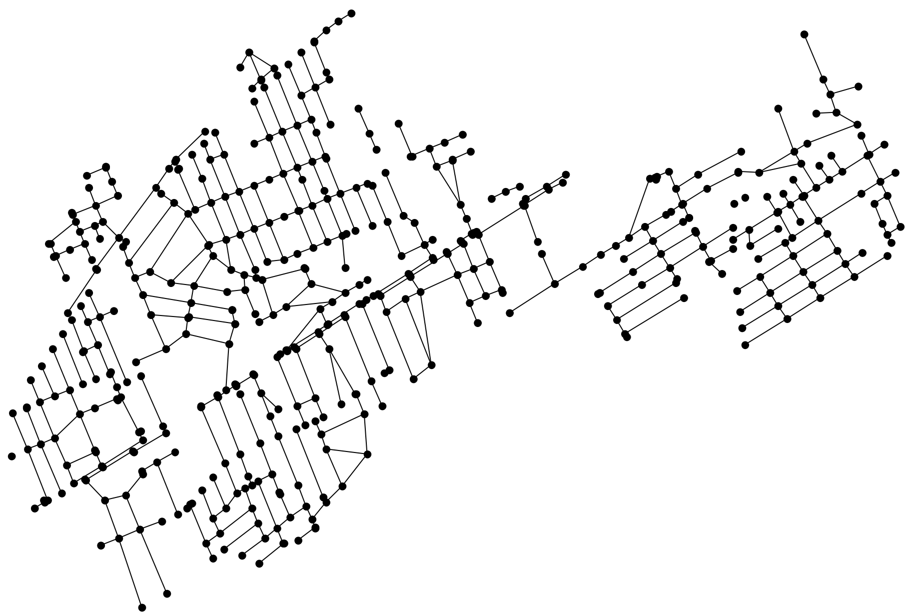

Figure 3. Network formed by 490 pipes in Groups 1 and 2

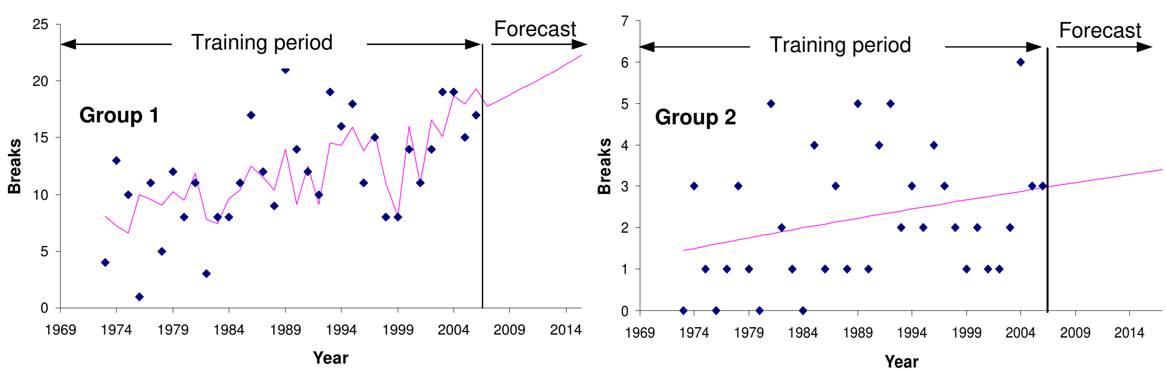

Figure 4. Trained models and forecasted breaks aggregated by year.

6.2 Pipe renewal planning

Corresponding to Step 1 (Section 5), planning period was selected as $T = 5$ years. Consequently, as can be seen in Figure 4, break forecast (using the coefficients from Table 1) was done for the 11 years 2007-2017 (forecast period that corresponds to $2T + 1$). Although Figure 4 illustrates only the aggregated number of forecasted breaks, I-WARP provides a break forecast for each individual pipe.

Corresponding to Step 2 (Section 5), we computed cost $C_{i,t}^{tot}$ for each pipe i in period $2T$+1. The unit costs used are provided in Tables 2 and 3. Zones in Table 3 represent different impact of pipe failure. Zone 1 represents low impact, e.g., industrial area; Zone 2 represents medium impact, e.g., residential area; and Zone 3 represents high impact, e.g., downtown area. Accordingly, each area is assigned different social cost of failure (Table 2) as well as an impact cost factor, used to multiply unit costs provided in Table 2. We consider a discount rate of $r = 2\%$, which is in line with typical social discount rates (as opposed to financial discount rates) appropriate for public projects.

Pipes for which t^* (i.e., $C_{i,t}^{tot}$ is minimum) occurs at year $t = 2T+1$ were not considered for replacement in planning period T and were therefore removed from the analysis pipe set. The subset of the remaining pipes comprised 105 (out of 490) individual mains. Their layout is illustrated in Figure 5.

We did not have real data on planned roadworks, instead we simulated roadwork schedule as follows. We assumed that the road above each of the 105 pipes would be renovated once in the 10 year period 2007-2016, in more or less equal portions each year. The year at which roadwork would be implemented was assigned by a random process using uniform distribution. Consequently, 57 (of 105) pipes saw planned roadwork during the 5-year planning period (Figure 5).

Table 2. Cost data

Item	Symbol	Unit	Value
Pipe replacement 150mm	Cr	\$/m	200
Pipe replacement 200mm	Cr	\$/m	250
Discount rate	r	(%)	2.0
Quantity for minimum discount	L_m^{min}	(m)	500
Quantity for maximum discount	$L_m^{\max}$	(m)	1,500
Maximum quantity discount	$d_m^{\max}$	(%)	10
Cost saving due to roadwork coordination	p_i	(%)	20
Cost of pipe repair	C_i^{rep}	(\$)	3,000
Cost of water loss due to failure*	C_i^{wat}	(\$)	300
Cost of mobilisation	M	(\$)	2,000

* Indirect cost of failure was considered zero

Table 3. Factors for cost assessment

	Zone 1	Zone 2	Zone 3
Impact cost factor	1	1.2	1.5
Social cost per break ($)	3,000	5,000	7,000

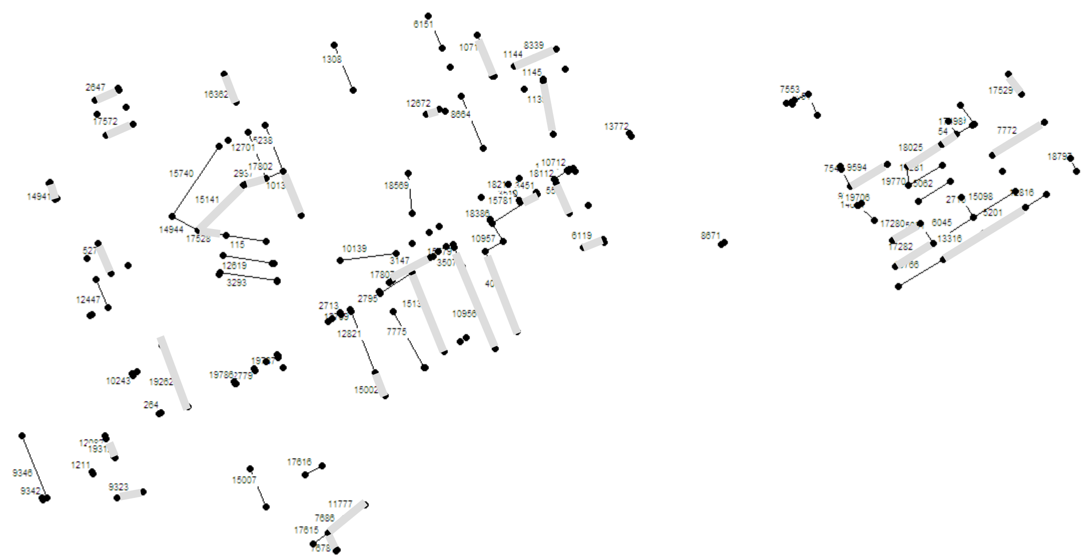

Figure 5. 105 candidate pipes for renewal (grey background = planned roadwork)

In order to demonstrate the efficiency of the optimization process, we first examined a renewal policy, whereby only pipes whose $C_{i,t}^{tot}$ is minimum for t = 1, 2, …5 are replaced (with no budget limitation). Table 4 provides a detailed summary of the outcome of this policy, to which we shall refer as the “baseline policy”.

Next we applied the optimization process with a budget constrained that is approximately equal to the total investment obtained in the baseline policy. Table 5 provides a detailed summary of outcome of this optimized policy. It is quite clear that the optimized policy is superior to the baseline policy, because while investing almost the same sum of money in replacement it allows for the replacement of an additional 772 m (more than 10% additional pipe length) of pipe and is expected to avoid one additional break compared to the baseline policy. It also provides a more balanced cash outlay compared to the baseline policy in which about half of the investment capital is expended in the first year.

Note that the total discounted cost in the optimized policy is higher than that in the baseline policy by about $24K. This is because the optimized policy encompasses 772m more replaced pipes compared to the baseline policy. One could therefore say that the optimal policy enabled the replacement of additional 772 meters of pipe at a marginal cost of about $31/m.

Table 4. Details of the baseline policy ($ values rounded to 1000)

	Year *t*					
	1	2	3	4	5	**Total**
Total length to replace $\sum l_i$ (m)	3,838	1,222	151	1,134	1,085	7,430
Total length to replace $\sum l_i$ (%)	30%	10%	1%	9%	8%	30%
# of pipes to replace n_t	40	8	3	9	5	65
# of pipes coordinated with roadwork	10	1	0	1	1	13
Savings on roadwork coordination (K$)	38	12	0	1	10	60
Savings due to contiguities (K$)	16	2	0	0	0	18
Saving due to quantity discount (K$)	115	26	0	22	19	182
Total savings$\sum C_{i,t}$(K$)	168	40		22	29	259
Expected # breaks avoided (relative to do nothing) during	13	3	0	1	0	17
Total discounted cost (K$)	959	320	44	312	290	1,926
Total investment in replacement (K$)	979	326	45	32	297	1,965

Table 5. Details of the optimised renewal policy ($ values rounded to 1000)

	Year *t*					
	1	2	3	4	5	**Total**
Total length to replace $\sum l_i$ (m)	1,057	1,381	2,553	1,392	1,819	8,202
Total length to replace $\sum l_i$ (%)	8%	11%	20%	11%	14%	
# of pipes to replace n_t	12	12	19	16	14	73
# of pipes coordinated with roadwork	4	5	8	5	5	27
Savings on roadwork coordination (K$)	34	49	60	40	49	232
Savings due to contiguities (K$)	0	2	10	4	4	20
Saving due to quantity discount (K$)	17	37	76	37	55	221
Total savings$\sum C_{i,t}$(K$)	51	88	146	81	108	374
Expected # breaks avoided (relative to do nothing) during *T*	13	3	0	1	1	18
Total discounted cost (K$)	251	322	605	334	438	1,950
Total investment in replacement (K$)	256	327	612	337	438	1,969

7. Summary and conclusions

A non-homogeneous Poisson process based model (I-WARP) is described, which considers three classes of covariates, pipe-dependent, time-dependent and pipe and time dependent. This model is used to forecast future water main breaks in each individual pipe. The forecasted numbers of break are then used for the efficient planning of water main renewal in a short to medium planning period. The planning takes account of life cycle costs associated with the pipes and considers aspects of economies of scale, including quantity discount, contiguity savings due to reduced mobilization costs and coordination with anticipated road works (hence the need for short to medium planning period). Renewal planning can be done with or without budget constraint, where budget constraint can be global (for the entire planning period) or annual. This non-linear scheduling problem is discretized and solved using multi-objective genetic algorithm (MOGA). A case study, comprising a network of about 500 individual pipes was used to demonstrate the modeling and the planning process.

The approach for planning the replacement of individual water mains, is currently limited to the consideration of structural resiliency (i.e., breakage frequency) of pipes and the economics of their replacement. In reality, other factors should also be considered as well, such as hydraulic, reliability, etc. More work is required to incorporate additional considerations into this approach.

Acknowledgement

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