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Improved modelling of 'long-term' future performance of drinking water pipes

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ABSTRACT

All people in developed countries benefit from running water in their homes. Providing this service calls for a significant quantity of pipes. To preserve water resources and ensure good network performance, it is important that pipes are renewed at the optimum time. This article presents the two main approaches currently used to plan pipe renewal, one using 'short-term' models (1–3 years), and the other employing 'long-term' models (more than 30 years). The majority of short-term models are fairly robust, whereas most long-term models currently in use are of questionable quality. The aim of this paper is to design a long-term model in compliance with short-term decisions and future goals. The method was tested using data from the largest water utility in Europe. This paper first estimates the past survival curve for water pipes, based on their age at removal from service. It is then used to make predictions about when pipes will require replacement. A number of performance indicators are then created, such as future renewal length, renewal rate, and future investment need. The proposed approach is different from existing long-term models because it is based on actual historical survival function.

Key words | asset management, decision making, network, survival functions, service life, water distribution systems

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INTRODUCTION

Context

Almost all people living in developed countries benefit from running water in their homes. Providing this service calls for a large number of pipes and other devices. In France, there were over 900,000 km of water pipes in 2014, with a combined value of 100 billion euros (MEDD 2004; Bouleau & Guérin-Schneider 2011; ASTEE *et al.* 2013a). All pipes experience some normal deterioration, which gradually reduces their performance. For this reason, a certain number need to be renewed each year. Pipes may also need to be renewed as a result of other external factors, such as roadworks, building work, and new legislation ('lead pipes must be removed', etc.).

To conserve water resources and obtain the best possible level of network performance (good water quality, few leaks and no excessive cost), pipes must be renewed at the optimum time. This should not happen too early, but at the same time, decision makers should not wait until a pipe has induced a lot of damage before replacing it. The basis for deciding the 'optimum' time for renewal is when as many goals (of the water utility) as possible are achieved.

Nowadays, asset management of drinking water pipes relies mainly on two time scales: in the 'mid-term', a multi-year investment plan fixes the annual budgetary envelopes to be devoted to renewal works over the next years (between 5 and 15 years depending on water utilities); and in the

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'short term', an annual programme of priority renewal works is drawn up within the fixed annual envelope.

Motivation and scientific question

Our study proceeded by a detailed literature review and the audit of the current practices of three European case studies (Syndicat des Eaux d'Ile de France (SEDIF), Grand Lyon, and Lausanne) that span diverse utility sizes and managements. This state of the art overview, that will be detailed further, leads to the important conclusion that budget planning and annual work programming have to be logically connected through a long-term approach (more than 30 years), and that the long-term approaches encountered in the literature, as well as in the practices of utilities, lack relevance. There is, hence, a strong need for a long-term methodology, the building of which constitutes our core scientific question.

This paper details in the first section the state of the art in matters of renewal work prioritization methods and 'long-term' approaches. A section is then devoted to a new long-term methodology, based on a probabilistic and statistical approach, centred on the analysis of observed service lifetimes of water pipes. A case study section presents and discusses the practical results. Conclusions are drawn at the end of the paper.

LITERATURE REVIEW

'Short-term' methods (<3 years)

We carried out an extensive literature review, as well as conducting interviews with managers of water reticulation networks. This work showed that commonly used short-term approaches are generally quite robust. Managers have developed their own decision processes, making use of a number of different models and computer applications to generate lists of pipes, displayed in order of necessity and opportunity for renewal. This process can essentially be broken down into five steps.

1. Estimating the probability of failure for each section of pipe: for malfunctions affecting water quantity, this estimation is carried out using computer applications such as 'Casses' or 'CARE-W-Poisson', which are based on probabilistic models (Malandain 1999; Le Gat 2014). They use as inputs actual historical data relating to failures (breaks, leaks, etc.), environmental conditions (soil, traffic, etc.), and pipe characteristics (material, length, diameter) (Eisenbeis *et al.* 2003). Other deterioration models (breaks, bursts, etc.) are available, for more examples see (Rajani & Kleiner 2001; Kleiner & Rajani 2001; Ugarelli & Bruaset 2010). For failures affecting water quality (red water, black water, etc.), the estimation can be achieved through the use of models such as Q-WARP (Liu *et al.* 2012).
2. Calculating the risk of damage associated with pipe failures: this includes, for example, the risk of customers losing their water supply (service interruption), the risk of traffic disruption in the case of a burst water main, the risk of flooding, landslides, etc. These calculations are generally carried out using programmes such as 'CARE-W-ARP' or 'CARE-W-Relnet'. First, the probability of failure detailed in step one is multiplied by repair time. This figure is then multiplied by the quantity, vulnerability, and value of certain vulnerable elements (consumers, road users, urban infrastructures, etc.) (Le Gauffre *et al.* 2002).
3. Calculating cost indicators: using the risk level generated in step two, it is possible to estimate the cost of potential damage as well as the cost of repairing or replacing pipes.
4. Risk and/or cost and/or performance indicators (infrastructure leakage index, etc.) are weighted by managers and entered into a decision model such as ELECTRE TRI (Roy 1996). Using this kind of model allows managers to input their preferences. The output of the model provides water managers with several groups of pipe sections, ranked in ascending order according to necessity of replacement. It is also possible to obtain a coloured geographic information system chart, again showing a range of pipes, from those in urgent need of replacement to those in less urgent need of replacement (Poinard 2006).
5. Considering external opportunities and constraints relating to service. These include coordination with other public services, such as roadworks, gasworks, urban development, etc. They can also be the result of external

elements such as fire safety (i.e. a need to increase the water capacity of certain pipes). By combining all of this information, water managers can create a definitive list of worksites (adjacent groups of pipes) to be carried out.

It is important to note that the steps detailed above, as well as the criteria taken into account, can change significantly from one service to another. There is also a wide variety of models and applications to carry out each step see (Jarrett *et al.* 2001; Saegrov *et al.* 2003; Burn *et al.* 2003; Engelhardt & Skipworth 2005; Marlow *et al.* 2009; Large 2013; Large *et al.* 2014). While the models are not perfect, the predictions generated by some of the better ones are very accurate. In view of this, there is little room for improvement with regard to existing short-term methods.

While short-term approaches are not the topic of this study, we believe it is important to detail the short-term decision process in order to better assess its relationship with the long-term process.

'Long-term' methods (30 years and longer)

The study showed that water utilities rarely use long-term approaches. The long-term methods we examined were often too simple, or insufficiently connected with short-term decision making. A number of models were identified (Cador (Cador 2002), Patrimoine Expert (Naldeo 2013), fixed future renewal rate (RR) (Freiburghaus 2012)). These models often consist of applying an arbitrary lifespan to a particular type of pipe, based on the advice of an 'expert'. This lifespan is then added to the date of installation of a given pipe to obtain its assumed date of removal from service. This approach is often not supported by those working in the field. However, it is used by one of the water utilities involved in this study, which applies expert lifespan figures to estimate the future annual renewal requirements for pipes made from five different types of material. The method is based on the arbitrary assumption that pipes must be replaced once they reach a given age. However, this is not an accurate assumption. Depending on conditions, some very old pipes may still be in perfect working order, while some relatively new pipes may be in poor condition. In addition, there is no link between 'expert' lifespan values and the short-term decision process, which essentially defines the age at which a pipe will be removed from service.

One promising model is that used by Kanew (Herz 2002; Kropp 2013), PiREM (Fuchs-Hanusch *et al.* 2008), Nessie (AWWA 2010). Instead of assuming that pipes are automatically renewed once they reach a specific age, it uses a probabilistic distribution of the age of groups of pipes at the time they are removed from service (cf. famous bell curves). Neither of these German, Austrian, and Australian models is currently used by French water utilities. On the other hand, the main weakness of this particular model is that the survival curve for different pipes is not based on actual data from the network of water utilities, but constructed based on 'expert advice'. It is therefore questionable whether or not these survival curves are consistent with the past data obtained from the service in question, and whether they are relevant to the service's associated past short-term decision processes and future goals.

It is important to add that there are other long-term models see (Jarrett *et al.* 2001; Saegrov *et al.* 2003; Engelhardt & Skipworth 2005; Marlow *et al.* 2009; Large 2013). These other long-term models are generally based on a threshold in the number of failures that decision makers do not want to exceed. However, when we asked decision makers of our case study (SEDIF) what are their failure thresholds, they could not answer us. Therefore, we decided against those kinds of model.

Conclusion on the state of the art

To conclude, existing long-term models are disconnected from short-term actual practices. Moreover, the most effective way of protecting natural resources and improving network performance seems to start with a long-term approach (30 years or more in the future). By using this long-term approach, water utilities can select the correct strategy (length of pipe to be renewed, materials, risk prevention, etc.) to ensure that they meet their performance objectives (i.e. good quality water, few leaks, low price, etc.). Having defined their long-term goals, utilities can deduce their multi-year investment plan in the 'mid-term', typically over a period less than 10 years. For example, multi-year investment plans are designed to last: 5 years in SEDIF, France, 6 years in Grand Lyon, France and 10 years in Lausanne, Switzerland.

Following this, a short-term approach should be used to create a list of pipes requiring renewal the following year, ranked in order of necessity (ASTEE *et al.* 2013b).

METHODOLOGY

Preliminary actions

An extensive review of relevant literature was carried out (Large 2013). Following this, interviews were conducted with professionals (managers of water reticulation network) from three European water utilities: the SEDIF, the communauté urbaine de Lyon (Grand Lyon), and the Service des Eaux de Lausanne (eauservice). The networks overseen by these water utilities have total lengths of 8,300 km, 3,900 km, and 900 km, respectively. Data relating to pipe sections, failures, and local environments were collected for each of these networks.

From this state of the art, a key scientific question was raised: is it possible to build a long-term model for a water utility which is linked with their existing short-term decision processes?

To go beyond this state of the art and answer our core scientific question we decided to create a new long-term model which could improve the current long-term methods. We elaborate a new long-term method (>30 years) to help water managers decide what type of work to carry out (length of pipe which will be renewed, what kind of material will be renewed, lead pipes having priority, and so on), linked with their existing short-term decision processes and specific long-term goals. Our long-term model is closely linked with the short-term models since it is based on actual historical data.

To compensate for the shortcomings of long-term methods, and their lack of compatibility with short-term methods, our long-term model is based on three steps. We used data from an actual water utility, the SEDIF.

The first step was to reconstruct the past survival curve of pipes in SEDIF. The 'survival function' means the probability that a given length of pipe will survive (i.e. not be taken out of service) above a certain age (t). We then decided to apply the 'same as in the past' scenario. It works on the hypothesis that in the past, decommissioning ages were well chosen (good past survival curve) and the same distribution (survival curve) is applicable for future decisions. The third and final step was to simulate the consequences of that strategy on the resulting work to be carried out (pipe length, future RR) and the costs involved (investment).

Description of the method

The case study below is SEDIF. It is the biggest water utility in France, more than 4.3 million people consume water from SEDIF.

The first step of our new long-term model is to identify the past survival curve for the sections of pipe under study (as a function of age at removal from service) using observed data that have first been statistically corrected (to compensate for left truncation and right censoring).

Figure 1 illustrates the concepts of left truncation and right censoring. The random variable T stands for the service lifetime. If we followed a water main installed at age $t = 0$ and observed between ages a and b: all service lifetimes $T + a$ are unobservable, i.e. left truncated; the value $T = b$ is exactly observed when the actual decommissioning of the segment stops the observation; and any value $T + b$ is right censored.

There are no 'survival functions' based only on pipe deterioration. Survival curves created from observed data therefore inevitably include pipe replacement for multiple

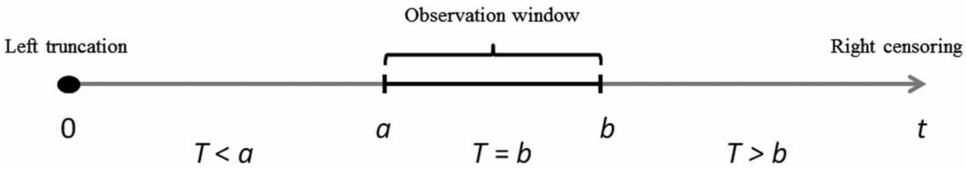

Figure 1 | Concepts of left truncation and right censoring.

reasons (coordination with roadworks, urbanisation, pipes in a poor state, changes in regulations, etc.). In this article, the 'survival function' means the probability that a given length of pipe will survive (i.e. not be taken out of service) above a certain age (t).

We can estimate the 'rough' survival function, $Sr(t)$, only for pipes already out of service (according to the inventory carried out on 31 December 2012) for the observation period (in this case 1995–2012). Sections of pipe are indexed as i. Each section has a length L_i and an age at removal from service b_i. Sections of pipe can be censored ($c_i = 1$) meaning that the date at which they were removed from service does not fall within the observation period, or uncensored, meaning that their removal from service took place within the observation period. $I\ \{\ldots\}$ is the indicator function. I will have a value of 1 if the conditions between the curly brackets are fulfilled, and 0 if not. 'Rough' probability distribution function, $D(t)$, is estimated first, followed by the 'rough' cumulative distribution function, $F(t)$, these are followed by the 'rough' survival function $Sr(t)$ (Equations (1) and (2)).

$$D(t) = \sum_i (L_i \times I\{c_i = 0\ \&\ b_i = t\}) / \sum_i (L_i \times I\{c_i = 0\}) \tag{1}$$

$$Sr(t) = 1 - F(t) = 1 - \sum_{k \leq t} D(k) \tag{2}$$

The dates of decommissioning of pipes in SEDIF were significantly available since 1995. Because of this, ages at removal from service were left truncated, with any pipes falling outside of the observation period being ignored. The 'rough' survival curve is therefore biased, and takes into account neither left truncated data nor right censored data (the date of removal from service for pipes still in service at the end of the observation period was unknown).

Well-known methods from human medicine and epidemiology were used to correct this biased sampling, and to create the non-biased 'empirical' survival function, $Se(t)$. We used the Turnbull method (Turnbull 1976; Le Gat *et al.* 2013) and the Kaplan-Meier method (Kaplan & Meier 1958). Both methods give exactly the same 'empirical' survival function.

As explained by Malm *et al.* (2012), this 'empirical' survival function not only shows the physical deterioration of a network over time (wear and tear), but is also a complex representation of past network decisions (varying levels of coordination with roadworks, varying levels of concern about the consequences of failures, etc.). These elements are more or less impossible to accurately reproduce. However, if the network manager applies the 'same as in the past' scenario (i.e. exactly the same objectives, mechanisms, and managements practices as before) this 'empirical' survival function can be our prospective survival function and still be used to calculate future performance indicators. In the second step we choose this scenario.

In the third step of our new long-term model, the prospective survival curve can then be used for a long-term estimation of the length of pipes requiring renewal each year, and the costs associated with that work.

Our method uses an iterative process to produce information on pipes laid in the past based on that relating to pipes currently in place. $C\theta$ represents all pipes (cohort) installed in a given year (θ). At the beginning of the process (2012), the year of installation (θ) ranges from 1,851 to 2012 (see Figure 2). For each year (N), each cohort has a length in service $\mathrm{LIS}_{C\theta}(N)$, a length out of service $\mathrm{LOS}_{C\theta}(N)$, an initial length $\mathrm{LINI}_{C\theta}(N)$ (see Equation (3)), and an age $t_{C\theta}(N)$. The survival function of a cohort $C\theta$ depends on its age the year N: $S[t_{C\theta}(N)]$.

$$\mathrm{LINI}_{C\theta} = \mathrm{LIS}_{C\theta}(N) + \mathrm{LOS}_{C\theta}(N) \tag{3}$$

First, we reconstruct past initial length $\mathrm{LINI}_{C\theta}$ of each cohort (Equation (4)). $S[t_{C\theta}(2012)]$ can be a direct output of the Turnbull method, or an output of a survival function like Herz (Herz 2002) adjusted on the Turnbull survival function.

$$\mathrm{LINI}_{C\theta} = \frac{\mathrm{LIS}_{C\theta}(2012)}{S[t_{C\theta}(2012)]} \tag{4}$$

Then, we predict the length of each cohort in 2013 (Equation (5)).

$$\mathrm{LIS}_{C\theta}(2013) = LINI_{C\theta} \times S[t_{C\theta}(2013)] \tag{5}$$

We want to predict the length of the new 2013 cohort. To maintain a constant length of pipes in service (8,300 km in SEDIF), Equation (6) can be used.

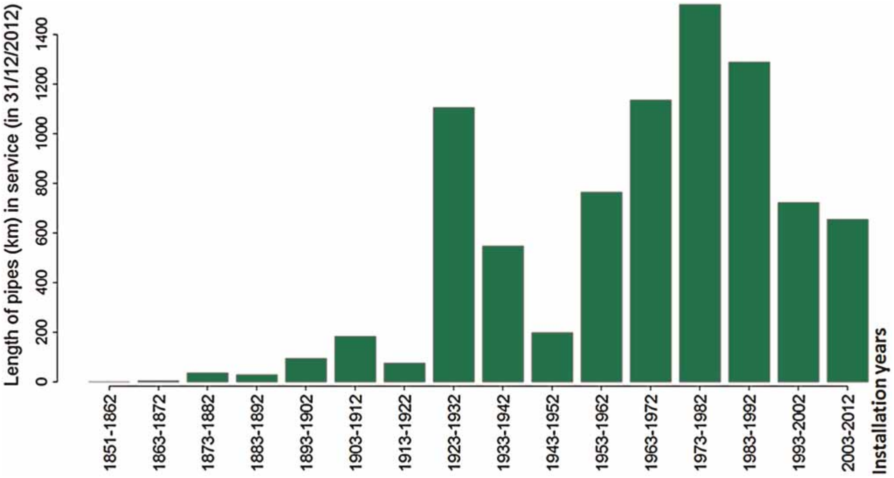

Figure 2 | Length (km) of pipes in service at the end of 2012 in SEDIF per decade of installation year.

$$\mathrm{LINI}_{C2013} = \mathrm{LIS}_{C2013}(2013) = \sum_{\theta=1,851}^{2012} [\mathrm{LIS}_{C\theta}(2012) - LIS_{C\theta}(2013)] \qquad (6)$$

The RR in 2013 is then deduced (Equation (7)).

$$\mathrm{RR}(2013) = \frac{\mathrm{LIS}_{C2013}(2013) \times 100}{\sum_{\theta=1,851}^{2015} \mathrm{LIS}_{C\theta}(2012)} \qquad (7)$$

This method is repeated year on year to provide predictions up until the desired future point in time.

RESULTS AND DISCUSSION

The results below relate to the SEDIF, which had around 8,300 km of pipes (transport and distribution) in service at the end of 2012 (Figure 2). Information relating to around 610 km of pipes no longer in service had been exhaustively

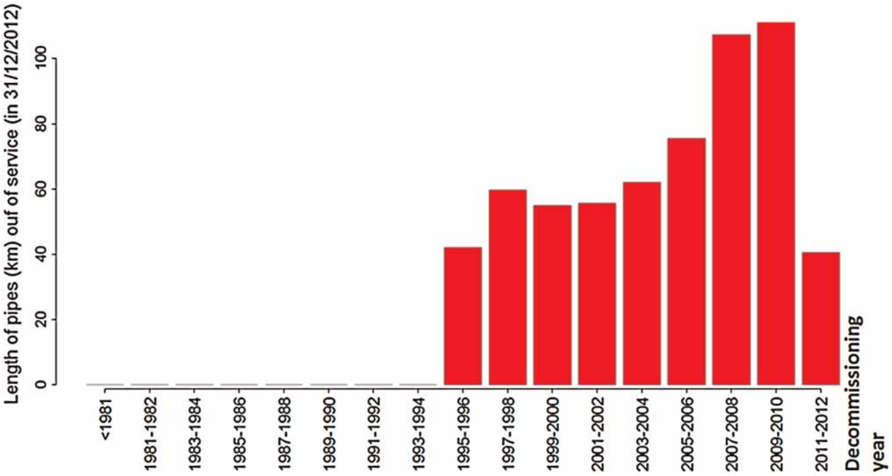

Figure 3 | Archived length (km) of SEDIF pipes out of service at the end of 2012, in 2-year increments based on decommissioning year.

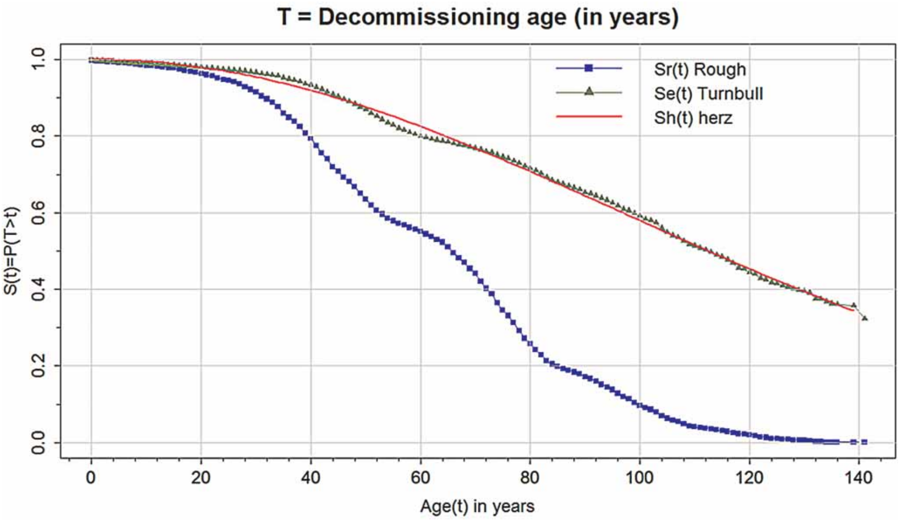

Figure 4 | S(t) = Probability that 1 m of pipe will not be removed from service once it reaches age t (all materials) – SEDIF transport and distribution network.

archived since 1995 (Figure 3). The usable observation period for this information is therefore 18 years, from 1995 to 2012. Dates of removal from service are truncated before 1995 and censored after 2012.

The empirical survival curve [$Se(t)$ Turnbull] (Figure 4) for pipe length is right shifted from the 'rough' survival curve [$Sr(t)$] due to right censored pipes not being taken into account in the 'rough' curve. For all past data, 1 m of pipe has a probability of 0.5 of surviving less than 105 years (Figure 4 and Table 1).

We adjusted a Herz survival function (Herz 2002) [$Sh(t)$ Herz] with the least squares method (see Equation (8)) to the SEDIF empirical survival curve [$Se(t)$ Turnbull], in order to have no gap in our function.

$$Sh(t) = (\alpha + 1)/(\alpha + e^{\beta \times t}) = 26/(25 + e^{0.031 \times t}) \tag{8}$$

Table 1 | Quartile of the empirical past survival function $Se(t)$ for transport and distribution pipe lengths (in SEDIF, and eauservice Lausanne), T, decommissioning age

	Age (t)	
$S(t) = P(T > t)$	**SEDIF**	**Lausanne**
0.75	74	43
0.5	105	53
0.25	145	65

Using this function (see red curve [$Sh(t)$ Herz] in Figure 4; the full colour version of this figure is available online at http://www.iwaponline.com/jws/toc.htm), it is possible to estimate future renewal requirements if the 'same as in the past' scenario is applied (see Equations (4)–(6)). The 1st of January 2013 was used as the starting point for all of the simulations. Figures 5 and 6 show two simulations. The desire future point in time is 2050 in the first simulation (cf. Figure 5) and 2120 in the second simulation (cf. Figure 6). Figure 5 is intended to represent the composition of the network in 2050 and Figure 6 is intended to represent the composition of the network in 2120. Each bar on these simulations is a cohort. We can clearly see the evolution between pipes in service and pipes out of service for each cohort when we compare the two simulations.

Using the 'same as in the past' scenario, the future RR for the SEDIF remains steady at between 0.5 and 1% (see Figure 7). The results are slightly higher than the RR applied by SEDIF in the immediate past, which averaged 0.44% for the period between 2005 and 2012, peaking at 0.8% in 2009. These rates are close to SEDIF's own goal of 1% annual renewal as of 2015.

Many researchers made a proposition for economical simulation (Dandy & Engelhardt 2006) and (Nafi & Kleiner 2010), therefore we decided to use the classical financial model with a discount rate. For this model relating to finance, it is assumed that the cost of renewing 1 m of

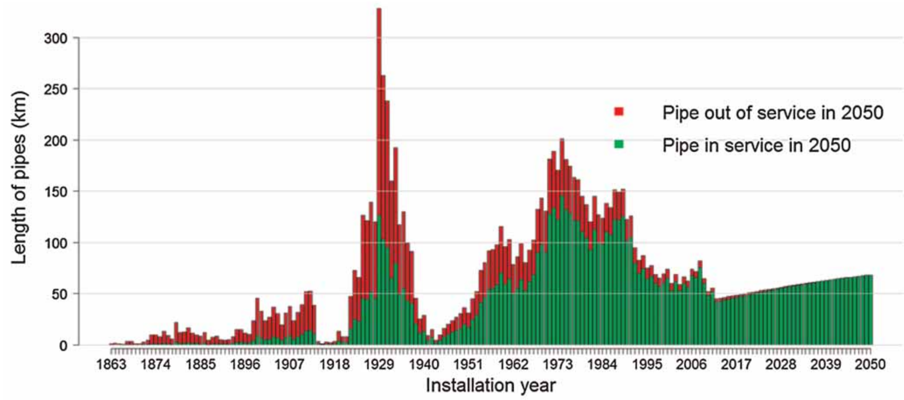

Figure 5 | Predicted installation lengths and years for pipe in-service in 2050 and pipes out of service in 2050, SEDIF transport and distribution network.

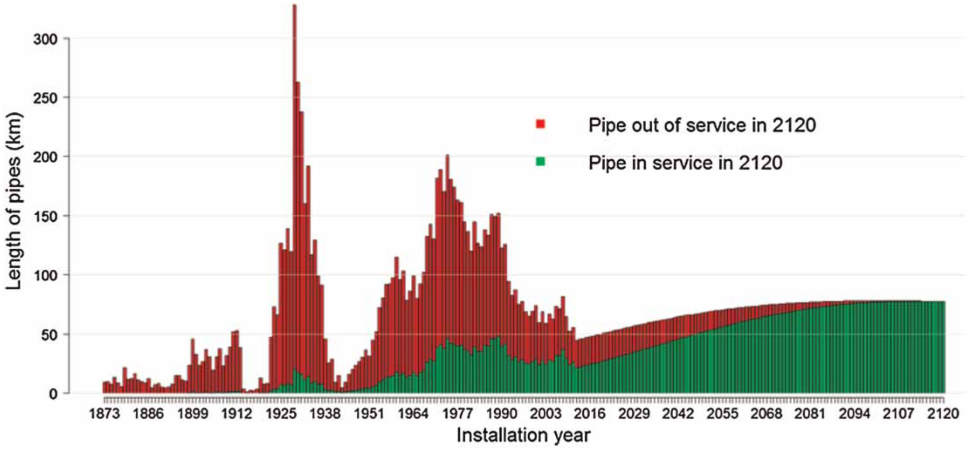

Figure 6 | Predicted installation lengths and years for pipe in-service in 2120 and pipes out of service in 2120, SEDIF transport and distribution network.

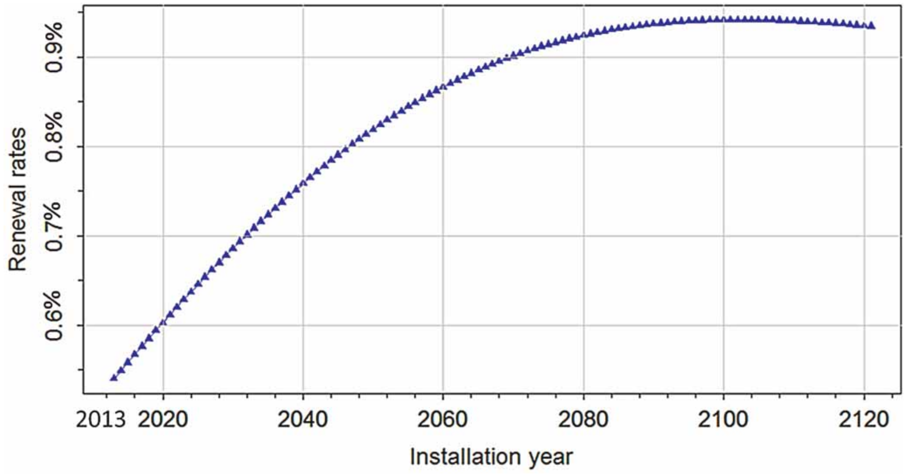

Figure 7 | Prediction of SEDIF future RRs from 2013 until 2120.

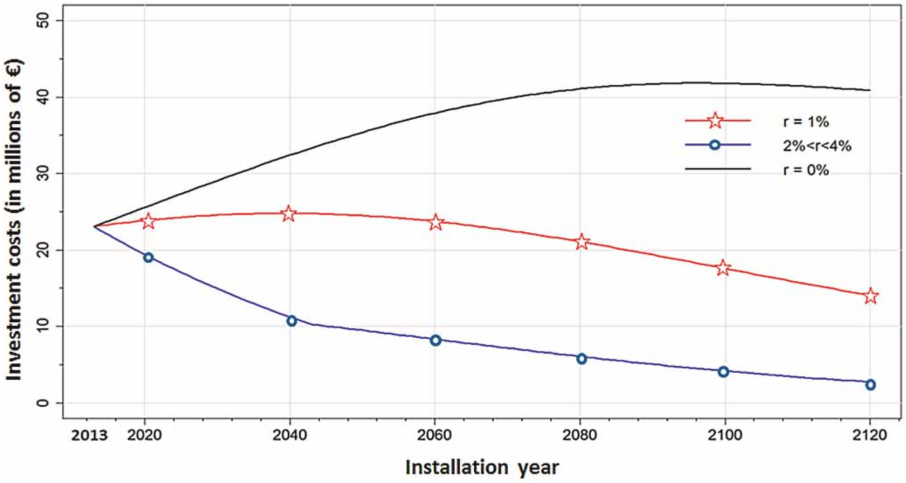

Figure 8 | Prediction of required renewal cost| (NPVC) between 2013 and 2120 (in millions of €), with three different discount rates (transport and distribution SEDIF network).

pipe is 530€ (500€ (including project management and related studies for a 100 mm diameter cast iron pipe) +6% (taking into account the diversity of diameters in SEDIF)). Based on the work of Hardelin & Marical (2011) relating to values of the discount rate (r_k), we chose to perform three budget simulations. We decided to calculate the net present value of investment costs (NPVC) each future year of the simulation (see Equation (9)). One with a discount rate equal to zero, a second with the discount rate set by French 'Commision Général au Plan' (Lebègue 2005) from 4% (2013–2043) and then decreasing after 2043 (asymptotically to 2%), and a third using a fixed discount rate of 1%. k is extra year(s) (Equation (9)) in order to reach the desired future point in time. In Figure 8, k varies from 0 to 107 years.

$$\mathrm{NPVC}(2013 + k) = \frac{\mathrm{Cost}(2013 + k)}{(1 + r_k)^k} \tag{9}$$

In budgetary consequences, the discount rate has a strong financial impact on the long-term. Therefore, the scenario with discount rate equals to zero seems most suitable. This scenario returns a peak in spending of 41.8 million euros in 2096 for pipe renewal within the main network (excluding connections) (see Figure 8 – black curve). This is interesting to compare with investments made by SEDIF in 2012 (public work only) which amounted to 19.6 million euros (SEDIF 2012).

The results of the corrected empirical survival curve $Se(t)$ for SEDIF should be placed in perspective with the result of those applied to another water service (eauservice Lausanne) (see Table 1). The results show that past pipe survival depends on management practices. For example, eauservice Lausanne has a higher average RR of 1.3% per year, meaning that the average pipe age at removal from service, in 2012, was half that observed for SEDIF.

It is clear that short-term management practices have significant influence on the past survival curve. However, managers of large water networks apply very different management practices to transport networks (diameter greater than 300 mm) and distribution networks (diameter less than or equal to 300 mm, excluding connections). (These definitions of the transmission network and the distribution network are those of the SEDIF.) It would therefore be useful to stratify survival curves by diameter, to see whether there are any particular differences. It could also prove fruitful to stratify by type of material or location. This will be tested at a later date.

CONCLUSION AND PERSPECTIVES

Following extensive consolidation of data from analysis of different management practices, the use of a long-term estimation method based on survival curves calculated with observed data led to more precise results than the classical method (i.e. Cador method). The next logical step is to simulate the effects of such a strategy on the future development of other performance indicators, allowing water managers to judge whether or not this approach is consistent with their particular objectives. For example, it could be possible to calculate indicators relating to expected maintenance costs, expected number of failures, etc.

Moreover, all pipes could be stratified based on relevant variables, such as type of material, diameter, and length. This would provide a survival curve per group of pipes, which could then be used to refine indicator calculations and better understand past decisions.

It is important to point out that this method can also be used on smaller networks without issue. Indeed, one of the case studies outlined in this paper took place on a medium network (900 km) in Lausanne, Switzerland.

Another way in which this particular method could be developed would be to move away from the 'same as in the past' scenario and focus instead on optimum scenarios. This would be achieved in two steps. First, a detailed analysis of short-term decision processes would be carried out, which would then be used to examine how the wide variety of causes leading pipes to be removed from service contribute to the construction of the survival curves observed.

The survival curves would then benefit from a correction of the effects of decisions taken at the work planning stage. The second step in the process would be to create new operational survival curves, in which the key elements governing the decision process would be explicitly represented. This could include, for example, the percentage of work carried out based on poor state versus the percentage carried out in coordination with roadworks. On this basis, it would be possible to estimate how different strategies (for example that of taking greater advantage of roadworks to access pipes) affect long-term performance.

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