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Decision support tools: Review of risk models in drinking water network asset management

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ABSTRACT

An objective of infrastructure asset management of drinking water network is to minimize risks (service outage, or disruption of vehicular traffic...). However there are several methods to assess their frequency. This paper first discusses the different models used in predicting the structural deterioration, because it is a compulsory preliminary step to calculate risk. Risk models for service outage are then discussed.

INTRODUCTION

Most developed countries in the world have opted to transport drinking water to households via long networks of pipes, which are expensive to install and maintain. The total length of water pipes installed in France is approximately 900,000 km, compared with around 300,000 km in England and Wales. Underground pipe networks represent more than 80 % of the total asset value for water distribution systems, and their management is therefore an important issue for water utilities (Renaud et al., 2012).

The overall objective of a water distribution system is to supply each consumer with enough good-quality water. The safety of the water network should be considered, and the overall costs should be acceptable. Regarding these objectives : i) *enough water* means fulfilling pressure and water demands. ii) *water quality* must comply with the established drinking water regulations and standards. iii) *safety* should be considered by means of reliability analysis and risk analysis. Thus, in practice water asset management is a complex multicriteria problem since managers must prevent or minimize damage: service outages, disruption of surface traffic (caused by maintenance works or water main bursts), flooding, interruption of business activities...

In order to help managers to deal with safety issues, a number of software applications have been developed during the last twenty years, usinge integrated

models for risk evaluation(*i.e.* the level of potential damage due to some unexpected events). Nevertheless the models in these software do not assess the same risks and not in the same way.

Decision support tools for the management of drinking water pipes are often composed of several interrelated models (see figure 1). In the following, we will consider four families of models :

- M1 are models to predict the degradation of the basic functions of the pipes. For example, in estimating the future failure rate due to pipe collapse, or the number of pipes with ferruginous red water.
- M2 are risk models, *i.e.* they forecast the potential damage when vulnerable elements (water users, vehicles, goods, etc.) are affected by hazard (break, leakage, red water ...).
- M3 are financial and economic models, they can monetize damage costs, repair costs, replacement costs, but also the benefits (which are often avoided damage or user satisfaction). These costs and benefits can be calculated from the point of view of the manager but also from the point of view of the whole society.
- M4 are decision models. They allow to take into account the priorities and decisions.

It is important to note that, at short term scale, the output of M1 are usually M2 inputs. Similarly, the outputs of M2 are M3 inputs, and M3 outputs are part of M4 inputs (see Figure 1). We will focus in the following on M2 (risk) models.

PIPE FAILURE MECHANISMS

Pipe condition is the cumulative effect of many factors acting on the pipe (Liu et al., 2012). Al-Barqawi and Zayed (2006) classified these factors into three categories: physical, environmental, and operational, as depicted in Figure 2. (Ana and Bauwens, 2010) explain that the occurrence and propagation of defects and the rate of structural deterioration are affected by these factors. The availability of accurate and sufficient amount of data on these factors plays a fundamental role in the development of many pipe deterioration and risk models.

RISKS INDUCED BY PIPE FAILURES

The word ”risk” (R) has a broad meaning (Taillandier, F., 2009). In the field of infrastructure asset management, it refers to the possible occurrence of an event, which may be intentional or unintentional, and can lead to the loss of an object, or any other kind of damage. According to French regulations on hazardous industrial installations (Circulaire IC, 2005), this definition involves three physical components: i) hazard, ii) vulnerable element, and iii) damage.

Software name (country) \ Models	M1 deterioration	M2 risk	M3 economic	M4 decision
W-PIPER	X			
D-WARP	X			
Q-WARP	X			
I-WARP	X			
T-WARP	X			
PARMS priority	X			
CARE-W-PHM	X			
CARE-W-Poisson	X			
CARE-W-NHPP	X			
Casses	X			
PRMS	X			
CARE-W-RelNet		X		
CARE-W-FailNet		X		
Criticité		X		
SynerGEE Rel. A.		X		

Software name (country) \ Models	M1 deterioration	M2 risk	M3 economic	M4 decision
Grille MS7				X
NESSIE curve			X	X
Patrimoine expert			X	X
GAnetXls			X	X
CARE-W-ARP		X	X	X
SIROCO		X	X	X
WiLCO		X	X	X
PARMS planning		X	X	X
MOSARE	X	X		X
Vision	X		X	X
KANEW	X		X	X
PiReM Drinking Water	X		X	X
PREVOIR Canalisation	X	X	X	X
Aware-P	X	X	X	X

Figure 1. Four different models in software for drinking water asset management

i) Hazard (H) is an intrinsic property of a substance (lead...), a technical system (pipe failure...), or an organism (bacteria...) susceptible to cause damage to a vulnerable element.
ii) Vulnerable elements (V) are individuals (consumers, road users...), goods (houses...), or components of the environment likely to suffer damage in certain circumstances, because of exposure to a hazard.
iii) Damage (D) means harm to a physical component (crack, spoil) or a person (physical, or psychological injury), caused by a third party. The division of risk into these three aspects (H/V/D) will provide a reading grid to compare risk models in the following sections.

Risk models (M2) can be classified according to the vulnerable elements impacted. For instance :

1. the presence of a leak or work (repair or replacement of pipe) on the network can impact *consumers* who have less or no water in the tap.
2. the presence of a leak or work on the network can impact *road users* (car, bus, tram etc .). This induces road cuts and traffic congestion.
3. huge leaks can flood *housing or industrial areas*.
4. ferruginous red water or black water (rich in manganese) can reach the *consumer*'s tap .
5. *residents* can be bothered by noise or dust during work, etc.

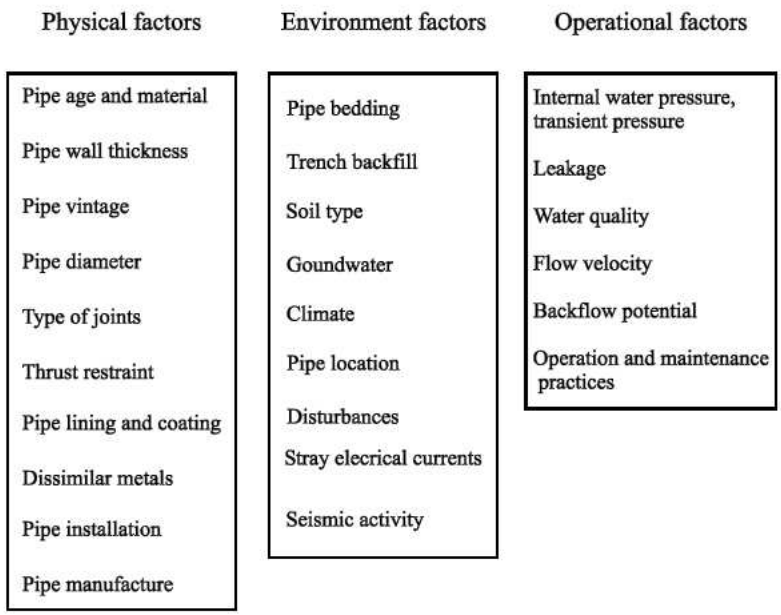

Figure 2. Factors Contributing to Water System Deterioration (Al-Barqawi and Zayed, 2006).

For example, some models are able to predict the first risk of having insufficient water, *i.e.* interrupting water supply to consumers, hospitals, businesses, fire hydrants... (*cf.* PARMS, CARE-W, Criticite, Aware-P...). The indicators and models used by these different applications vary in terms of complexity. Some programs use hydraulic models (*cf.* CARE-W-RelNET), while others do not (*cf.* PARMS). However, risk is in all cases are constructed in the same way: a) Probability (P) of failure $\bigotimes$ b) intensity (I) of the failure $\bigotimes$ c) at least one consumer-related characteristic (vulnerable element) : quantity (Q), sensitivity (S) or value ($) [see Eq. (1)].

$$R_D = (P_H \times I_H) \times (Q_V \times S_V \times \$_V) \tag{1}$$

where :

- probability measures the likelihood of occurrence, expressed by a number between 0 and 1, 0 indicating an impossibility and 1 an absolute certainty (ISO 73, 2009).
- Intensity reflects the importance of a phenomenon (Dauphine, A., 2001).
- Quantity is a weight, volume, number that determines a material portion, a collection of things (Jeuge-Maynart, I et al., 2011).
- Sensitivity is a factor of proportionality between the effects that vulnerable elements face and the damage suffered (Circulaire IC, 2005).
- Value is a generic concept, describing what worth an object that can be traded, sold, and, in particular, its price. Importance attached in price subjectively to

something. (Jeuge-Maynart, I et al., 2011). Value can be used for non-tangible components (like human life or environment), but there is here a matter for discussion.

All of these risk indicators require the probability of future failure to be estimated. However, this calculation is made difficult by a number of different factors. Therefore powerful deterioration models are needed to assess this probability.

DETERIORATION MODELS

Preliminary

Deterioration models allow the estimation of future probable failure rate. A distinction can be made between deterministic models and statistico-probabilistic models.

Deterministic models		Statistico-probabilistic models	
Name	Origin	Name	Origin
Kanew-linear	(Kropp, 2013)	Weibull	(Eisenbeis, 1994)
Kanew-exponential	(Kropp, 2013)	Poisson	(Malandain, 1999)
Shamir et al. 1979	(Shamir et al. 1979)	NHPP	(Rostum, 2000)
Clark et al. 1982	(Clark et al. 1982)	LEYP	(Le Gat, 2009)
Vision	(UKWIR, 2009)		

Figure 3. Origins of some deterministic and statistico-probabilistic models

Deterministic models

Determinism is a school of thought which advocates that the sequence of events and phenomena is due to the principle of causality. Links can often be described by physical or mathematical equations whose parameters can be determined from actual data or expert opinion.

These models take into account different factors in order to predict future failure rate but all include at least the age of the pipes (see figure 4).

All these models can be used over the long term and generally either at the scale of the network or at the scale of a group of pipes (physical district metered area or cohort of same material).

Deterministic models are quite simple but doesn't fit very well. For example, the model (Clark et al., 1982) which seems to be the most complex reflects reality with a R^2 = 0.47 (for a large water utility on short term) [1] (Clark et al., 1982) . However their simplicity makes them easy to be introduced in long-term models that contain other useful options for the manager (calculation of renewal and budget need) (see Kanew software).

[1]the R^2 or coefficient of determination indicates how well data points fit a line or curve. It varies from 0 (no fit) and 1 (100 % adjustment).

Factors \ Models	Kanew-linear	Kanew-exponential	Shamir et al. 1979	Water Uti	Clark et al. 1982	Vision
Age (time)	X	X	X	X	X	X
Material				X	X	
Soil type					X	
Water pressure					X	X
Length						X
No of failures			X			X

Figure 4. Factors taken into account for failure prediction in different deterministic models

Statistico-probabilistic models

In this section we will present exclusively statistico-probabilistic models. These models rely on the theory of probabilities, ie the mathematical study of phenomena characterized by randomness (evolution in the number of failures of a pipe / or monitoring the age at the end of service life of a group of pipes). A group of pipes with the same factor (see figure 2) do not all have the same failure rate. There is a residual part that can not be explained by these factors. The statistico-probabilistic models formalize this residual part by a probability distribution. To estimate the parameters of these models, we first made statistics on actual past data. The method of maximum likelihood (or log-likelihood) is the most commonly used to estimate the parameters of these models.
The input data of these models are : the characteristics of the pipes, their environment (traffic, climate, soil etc.) (see figure 2) and their failures (failure time, description, ID pipe, etc .)

Statistico-probabilistic models have the ability to greatly improve the prediction quality of failure rate when compared with deterministic models. All this models came from a theory developed by (Cox, 1972). Statistico probabilistic software for failure prediction usually contain a single model. For instance CARE-W-PHM contains the Weibull model (see figure 5). However some software contain several option for modelling the statistical distribution of the random variable that the user can use according to the amount of input data available. Thus, in the MOSARE software if the water utility has not a lot of data, the method implemented is a multi-criteria analysis, if the water utility has more data, the Poisson model is applied and if there is much

data it will be the Weibull model.

Software/ Models	Weibull	Poisson	NHPP	LEYP
CARE-W-PHM	X			
CARE-W-Poisson		X		
CARE-W-NHPP			X	
Casses				X
Aware-P			X	X
SIROCO				X
PARMS		X		X
MOSARE	X	X		
PREVOIR				X
I-WARP		X		

Figure 5. Model implemented by the software

Models	Prediction of failure rate	Hierarchy of pipes by probable failure rate
Weibull	-	+
Poisson	+	-
NHPP	+	-
LEYP	+	+

Figure 6. Advantages and disadvantages of different models

The Weibull model produced a good ranking of pipes by the future probable rate (relative value) of failure compared to reality. Poisson models and NHPP (Non Homogeneous Poisson Process) have a good prediction of the (absolute value) failure rates compared to reality. LEYP (Linear Extended Yule Process) model is a model which synthesizes these two advantages (see figure 6) (Eisenbeis et al., 2002a; Eisenbeis et al., 2002b; Eisenbeis et al., 2003; Eisenbeis et al., 2004; Le Gat, 2009; Martins, 2011).

RISK MODELS

Preliminary

We presented above five different risks classified regarding the vulnerable element that can be impacted. We will now focus on models able to assess the risk of having insufficient water (see figure 7).

Model concept

In this risk calculation :

Models	Origin	Country
CARE-W-ARP	(Le Gauffre et al., 2002)	France
CARE-W-ReINET	(Viscor, 1997)	Czech Republic
Criticité	(Bremond, 2005)	France
PARMS	(Burn et al. 2003)	Australia
Aware-P	(Vitorino et al. 2012)	Norway & Portugal

Figure 7. Origin of risk models

- vulnerable elements considered are the consumers of water
- the hazard considered is a failure inducing a decrease in water flow or in the worst case interrupting water supply to consumers
- the severity of the damage potentially caused depends then on two dimensions of hazard: its probability of occurrence and its intensity (time to repair the failure); and on three dimensions of vulnerable elements affected by hazard: their quantity, their sensitivity, and their value.

Discussion

All indicators presented in Figure 8 do not necessarily take into account all the aspects presented above and in equation 1 (see empty cells in Figure 8).
For example, HCl characterizes the severity of the damage when the probability of failure occurs is 100%. HCI is the only indicator in which there is a real hydraulic calculation.
IE however is not really an indicator characterizing the potential damage because this indicator does not account for any parameter related to the consumers.
C is the most comprehensive indicator of those presented above since all dimensions are covered. However for reasons of simplicity the same coefficient takes into account both sensitivity and value dimension.
Finally only $C_{customer}$ contains a coefficient which takes into account the monetized value of users.

Risk / Software	Risk Indicator	Hazard (failure)		Vulnerable elements (consumers)		
		Probability	Intensity	Quantity	Sensitivity	Value
CARE-W-ARP	PCWI	X	X		X	
CARE-W-ARP	PWI	X	X	X		
CARE-W-ReINET	HCI	X		X		
Criticité	C	X	X	X	X	X
Water Uti	IE	X	X			
PARMS	$C_{customer}$	X	X	X		X
Aware-P	UDY	X	X	X		

Figure 8. Factors taken into account in risk calculation in different models of software

SUMMARY AND PERSPECTIVES

There is a high variability of the pipe service lives. While some pipes installed 150 years ago are still in full working order, some younger pipes may have a high failure rate and need to be replaced soon. The broad range of explanatory factors calls for the use of a powerful prediction models. In the software applications studied, models used can be divided into two categories: i) On the one hand, there are models able to make long term calculation ($>$ 50 years). These models consider the network as split into broad groups of pipes, each group being characterized by a given lifetime, either in a deterministic (*cf.* NESSIE) or probabilistic (*cf.* the Herz function (Herz, 2002) in KANEW, PiReM...) way. ii) On the other hand there are models able to make short term ($<$ 5 years) calculations. These tools estimate future failure rate of each pipe segment through statistical/probabilistic models like Weibull (followed by Monte Carlo simulation), Poisson regression (*cf.* I-WARP), Non Homogeneous Poisson Process (*cf.* CARE-W-NHPP) or Linear Extended Yule Process(*cf.* PARMS-priority, Casses, Aware-P...).

All these models have their own set of advantages and disadvantages. The advantage of the first category is that they are able to assess the consequences in terms of service quality (performance) and can include long term financial calculations such as the whole life cost or cost benefit analysis, whereas the advantage of the second is that they hierarchize the network segments according to their risk level, in order to optimally allocate the annual renewal budget. The disadvantage of the first category is that residual lifetimes are based on expert knowledge, not on real water utilities' past data, whereas the disadvantage of the second is that future failure probability is only an extrapolation of what happened in the past.

A pivotal research question is then raised: is it possible to build long term survival functions in compliance with risk-based short term decision models?

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