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

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Abstract: Almost all people living 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 sections of pipe are renewed at the optimum time. An objective of infrastructure asset management of drinking water network is to minimize risks (service outage, or disruption of vehicular traffic, or flooding etc.). However there are several methods to assess their frequency. This article first discusses the different models used in predicting the structural deterioration, because it is a compulsory preliminary step to calculate risk. We explain that probabilistic deterioration models are more complicated and more precise models than deterministic deterioration models. Then this paper focuses on the risk of consumers having less or no tap water induced by pipe failures.

Key words: Drinking-water, failure, models, network, pipe, probability, risk, software.

1. 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, using 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 (Table 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 etc.).

- 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 outputs of M1 are usually M2 inputs. Similarly, the outputs of M2 are M3 inputs, and M3 outputs are part of M4 inputs (Table 1). We will focus in the following on M2 (risk) models.

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

Models / Software name (country)	M1 deterioration	M2 risk	M3 economic	M4 decision	Models / Software name (country)	M1 deterioration	M2 risk	M3 economic	M4 decision
W-PIPER (USA)	X				Grille MS7 (F)				X
D-WARP (CDN)	X				NESSIE curve (AUS)			X	X
Q-WARP (CDN)	X				Patrimoine expert (F)			X	X
I-WARP (CDN)	X				GAnetXls (GB)			X	X
T-WARP (CDN)	X				CARE-W-ARP (F)		X	X	X
PARMS priority (AUS)	X				SIROCO (F)		X	X	X
CARE-W-PHM (F)	X				WiLCO (GB)		X	X	X
CARE-W-Poisson (F)	X				PARMS planning (AUS)		X	X	X
CARE-W-NHPP (N)	X				MOSARE (F)	X	X		X
Casses (F)	X				Vision (F)	X		X	X
PRMS (USA)	X				KANEW (D)	X		X	X
CARE-W-RelNet (CZ)		X			PiReM Drinking Water (A)	X		X	X
CARE-W-FailNet (F)		X			PREVOIR Canalisation (F)	X	X	X	X
Criticité (F)		X			Aware-P (N) (P)	X	X	X	X
SynerGEE Rel. A. M. (USA)		X							

2. 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 1. (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.

3. RISKS INDUCED BY PIPE FAILURES

The word "risk" (R) has a broad meaning (Taillandier, 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.

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.

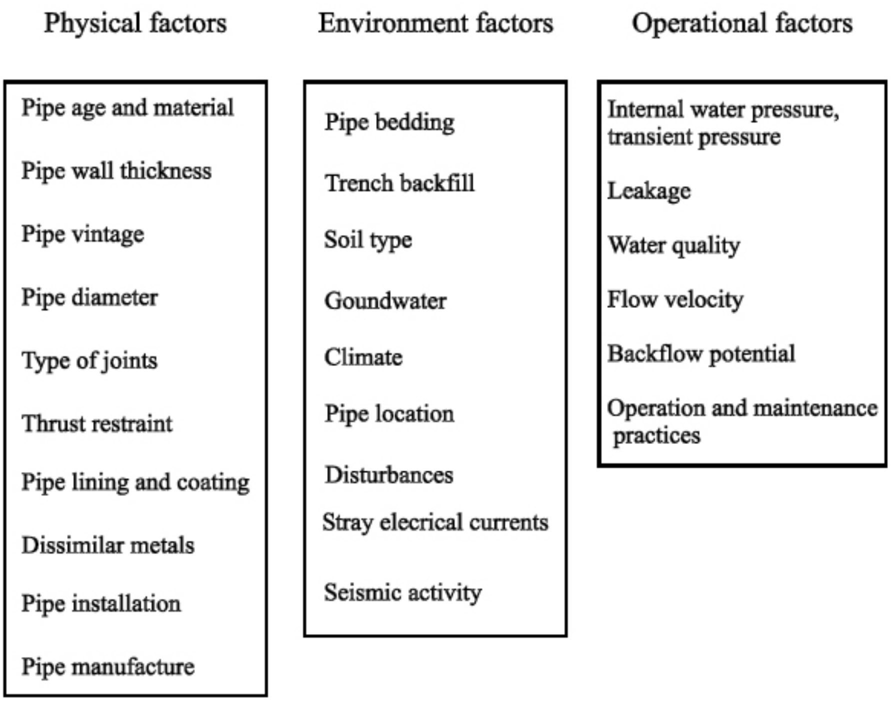

Figure 1. Factors Contributing to Water System Deterioration (Al-Barqawi and Zayed, 2006).

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.

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 etc. (*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 in all cases are constructed in the same way: a) Probability (P) of failure "times" b) intensity (I) of the failure "times" c) at least one consumer-related characteristic (vulnerable element): their quantity (Q), their sensitivity (S) or their value ($) (Eq. 1).

$$R_D = (P_H \times I_H) \times (Q_V \times S_V \times \$_V) \quad (1)$$

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, 2001).
- Quantity is a volume or a number that determines a material portion or a collection of things (Jeuge-Maynart 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 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.

4. DETERIORATION MODELS

4.1 Preliminary

Deterioration models allow the estimation of future probable failure rate. Rajani and Kleiner (2001), Kleiner and Rajani (2001), Marlow et al. (2009) and Ugarelli and Bruaset (2010) made very good reviews of deterioration models.

A distinction can be made between deterministic models and probabilistic models (cf. Table 2).

Table 2. Origins of some deterministic and probabilistic models.

Deterministic models		**Probabilistic models**	
Name	Origin	Name	Origin
Shamir et al. 1979	(Shamir et al. 1979)	Weibull	(Eisenbeis, 1994)
McMullen, 1982	(McMullen, 1982)	Poisson	(Malandain, 1999)
Walski et al. 1982	(Walski et al., 1982)	Mailhot	(Mailhot et al., 2000)
Clark et al. 1982	(Clark et al., 1982)	NHPP	(Rostum, 2000)
Jacobs et al. 1994	(Jacobs et al., 1994)	LEYP	(Le Gat, 2009)
Kanew-linear	(Kettler et al., 1995)		
Vision	(UKWIR, 2009)		
Kanew-exponential	(Kropp, 2013)		

4.2 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. The huge difference of deterministic models compared to probabilistic models is that, in the output of the models, only the average of the variable studied (here future number of failures) is taken into account.

These models take into account different factors in order to predict future failure rates but all include at least the age of the pipes (Table 3). Moreover even if the material and the diameter are not an input in the deterministic equation, these factors can be taken into account by creating partition of the pipe networks based on the material and on the diameter (Kanew, PARMS and other software). A partition of a set X is a division of X as a union of non-overlapping and non-empty subsets.

Table 3. Factors taken into account for failure prediction in different deterministic models.

Factors \ Models	Kettler et al. 1995	Jacobs et al. 1994	McMullen, 1982	Kanew-power	Vision	Shamir et al. 1979	Walski et al. 1982	Clark et al. 1982
Age (time)	X	X	X	X	X	X	X	X
Material							X	X
Diameter								X
Length		X			X			X
No of past failures					X	X	X	
Soil type			X					X
Water pressure					X			X
No of connections					X			

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 partitions of same material).

Deterministic models are quite simple but don'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). 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) (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).

4.3 Probabilistic models

In this section we will present exclusively probabilistic models. These models rely on the theory of probabilities, *i.e.* the mathematical study of phenomena characterized by randomness (evolution in the number of failures of a pipe, etc.). The coefficients of the equation can be determined from actual data or expert opinion. The huge difference between probabilistic models compared to deterministic models is that, in the model outputs, they generally take into account the mean, but also the median and the standard deviation of the studied random variable. 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.; Figure 1) 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 these 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 (Table 4). However some software contain several options 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.

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 (Table 5) (Eisenbeis et al., 2002a, 2002b, 2003, 2004; Le Gat, 2009; Martins, 2011; Le Gat, 2013).

Table 4. Model implemented by the software.

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		

Table 5. Advantages and disadvantages of different models.

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

5. RISK MODELS

5.1 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 (Table 6).

Table 6. Origin of some risk models.

Models	Origin	Country
CARE-W-RelNET	(Viscor, 1997)	France
CARE-W-ARP	(Le Gauffre et al., 2002)	Czech Republic
PARMS	(Burn et al. 2003)	France
Criticité	(Bremond, 2005)	Australia
Aware-P	(Vitorino et al. 2012)	Norway & Portugal
Scholten, 2013	(Scholten, 2013)	Switzerland

5.2 Model concept

In this risk calculation:

- 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.

5.3 Discussion

All indicators presented in Table 7 do not necessarily take into account all the aspects presented above and in Equation 1 (see empty cells in Table 7).

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.

Table 7. Factors taken into account in risk calculation in different models of software.

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-RelNET	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		
Scholten, 2013	R	X		X		

6. SUMMARY AND PERSPECTIVES

We presented above different risk indicators at the scale of the pipe segment. They are very useful when choosing which pipes or group of pipes need to be renewed. Indeed, there is a high variability of pipe service lives. While some pipes installed 150 years ago are still in full working order, some younger pipes may have a high risk (high failure rate and lots of vulnerable elements close) and need to be replaced soon. The broad range of explanatory factors calls for the use of powerful models.

In this article we only focus on the risk of consumers having less or no tap water. We could have focused on other risks like: i) road users impacted by traffic disruption induced by leaks or works; ii) flooding of urban infrastructures induce by leaks; iii) etc.

Moreover these risk indicators are at the scale of the pipe segment, but we could have calculated them at a larger scale like network as (Kanakoudis, 2004).

In order to make a risk calculation, two steps are compulsories.

1. First the future rate of failures must be estimated. In the software applications studied, models used can be divided into two categories:
   i) From one side, models can consider the network as split into broad groups of pipes, each group being characterized by a deterministic equation (*cf.* Kanew, Vision, PireM software

etc.). These models are more simple than probabilistic models, that is why they are more used to make long term calculations and decisions (> 50 years).

ii) From another side, there are probabilistic models. These tools estimate future failure rate of each pipe segment through statistical distribution [Weibull, Poisson (*cf.* I-WARP software), Non Homogeneous Poisson Process (*cf.* CARE-W-NHPP software) or Linear Extended Yule Process (*cf.* PARMS-priority, Casses, Aware-P software...]. These models are much more complicated and more precise than deterministic models, that is why they are mostly used to make short term (< 3 years) decisions.

2. Then characteristics of vulnerable elements around the pipes must be collected.

All these models and software have their own set of advantages and disadvantages. The advantage of deterministic models is that they can easily include long term financial calculations such as the whole life cost or cost benefit analysis, whereas the advantage of the second is that they make a precise hierarchy of 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 models with probabilistic estimation of failure rate?

REFERENCES

Al-Barqawi, H., and Zayed, T., 2006. Condition Rating Model for Underground Infrastructure Sustainable Water Mains. *Journal of Performance of Constructed Facilities*, 20(2), 126-135.

Ana, E. V. and Bauwens, W., 2010. Modeling the structural deterioration of urban drainage pipes: the state-of-the-art in statistical methods. *Urban Water Journal*, 7, 47-59.

Bremond, B., Laplaud, C., Huchin, B., De Massiac, J. C. and Renaud, E., 2005. *Systeme integre d'aide au renouvellement optimise des conduites adapte aux petites et moyennes collectivites : SIROCO*. CEMAGREF, G2C Environnement, 189.

Burn, S., Tucker, S., Rahilly, M., Davis, P., Jarrett, R. and Po, M., 2003. Asset planning for water reticulation systems – the PARMS model. *Water Science and Technology: Water Supply*, 3, 55-62.

Cador, J., 2002. *Le renouvellement du patrimoine en canalisations d'eau potable en France*. Universite de Caen, 18.

Circulaire IC, 2005. *Circulaire relative aux installations classees du 7 octobre 2005*. 18.

Clark, R. M., Stafford, C. L. and Goodrich, J. A. (1982). Water distribution systems: a spatial and cost evaluation. *Journal of the water resources, planning and management*, 108, 243-256.

Cox, D. R., 1972. Regression Models and Life-Tables. *Journal of the Royal Statistical Society*. 34, 187-220.

Dauphine, A., 2001. *Risques et catastrophes. Observer, spatialiser, comprendre, gerer*. Armand Colin.

Eisenbeis, P.,1994. *Modelisation statistique de la prevision des defaillances sur les conduites d'eau potable*. PhD thesis, Universite Louis Pasteur Strasbourg, France 190.

Eisenbeis, P., Le Gat, Y., Laffrechine, K., Le Gauffre, P., Konig, A., Rostum, J., Tuhovcak, L. and Valkovic. P., 2002a. *D3, CARE-W: WP2 Description and validation of technical tools, Report 2.1 models description*. Cemagref Bordeaux, INSA Lyon, SINTEF, NTNU, Brno University of Technology, 120.

Eisenbeis, P., Le Gat, Y. and Poulton, M., 2002b. *Failure forecast and hydraulic reliability models for rehabilitation decision aid*. International Conference for Computer aided rehabilitation of water networks (CARE-W), in Dresden Germany, November 1st., 97-106.

Eisenbeis, P., Laffrechine, K., Le Gauffre, P., Le Gat, Y., Rostum, J., Tuhovcak, L. and Valkovic. P., 2003. *D4, CARE-W : WP2 Description and validation of technical tools, Report 2.2 Tests and validation of technical tools*. Cemagref Bordeaux, INSA Lyon, NTNU, Brno University of Technology, 2003, 58.

Herz, R., 2002. *Developing rehab strategies for drinking water networks*. Dresden University of Technology, Germany Proceedings of the 9 DBMC International Conference on Durability of Building Materials and Components, 11.

ISO-73, 2009. *Management du risque, Vocabulaire*. International Organization for Standardization, Norme, ISO guide. 25.

Jacobs, P. and Kerney, B., 1994. *GIS development with application to cast iron water main break rate*. 2nd International conference of water pipeline systems, Edinburgh, Scotland.

Jeuge-Maynart, I., Girarc-Marinier, C. and Florent, J., 2011. *Le petit larousse illustre 2011*.

Kanakoudis, V. K., 2004. *Vulnerability based management of water resources systems*. Journal of Hydroinformatics. 06.2, 133-156.

Kettler, A. J. and Goulter, I. C., 1985. An analysis of pipe break in urban water distribution networks. *Canadian Journal of Civil Engineering*, 12, 286-293.

Kleiner, Y. and Rajani, B., 2001. Comprehensive review of structural deterioration of water mains: statistical models. *Urban Water Journal*, 3, 131-150.

Kropp, I., 2013. *Kanew software, version 4, manual*. 2013, 76 .

Le Gauffre, P., Laffrechine, K. and Rolf, B., 2002. *D6, CARE-W: WP3 Decision Support for Annual Rehabilitation Programmes, Report 3.1 Criteria for the prioritisation of rehabilitation projects*. INSA Lyon.

Le Gat, Y., 2009. *Une extension du processus de Yule pour la modelisation stochastique des evenements recurrents. Application aux defaillances de canalisations d'eau sous pression*. PhD thesis, Institut des Sciences et Industries du Vivant et de l'Environnement (AgroParisTech), France, 121.

Le Gat, Y., 2013. Extending the Yule Process to model recurrent pipe failures in water supply networks. *Urban Water Journal*, published online, 15.

Liu, Z., Kleiner, Y., Rajani, B., Wang, L. and Condit, W., 2012. *Condition assessment technologies for water transmission and distribution systems*. United States Environmental Protection Agency (EPA), 108.

Mailhot, A., Pelletier, G., Noël, J. F. and Villeneuve, J. P., 2000. Modeling the evolution of the structural state of water pipe networks with brief recorded pipe break histories: Methodology and application. *Water Resources Research*, 36(10), 3053–3062.

Malandain, J., 1999. *Modelisation de l'etat de sante des reseaux de distribution d'eau pour l'organisation de la maintenance : etude du patrimoine de l'agglomeration de Lyon*. PhD thesis, Institut National des Sciences Apliquees (INSA) de Lyon, France, 206.

Marlow, D., Davis, P., Trans, D., Beale, D., Burn, S. and Urquharta, A., 2009. (Eds.) *Remaining Asset Life: A State of the Art Review*. IWA publishing, 70.

Martins, A. (2011). *Stochastic models for prediction of pipe failures in water supply systems*. PhD thesis, Instituto Superior Tecnico, Universidade tecnica de Lisboa, Portugal, 85.

McMullen, L. D., 1982. *Advanced concepts in soil evaluation for exterior pipeline corrosion*. AWWA Annual Conference, Miami, USA.

Rajani, B. and Kleiner, Y., 2001. Comprehensive review of structural deterioration of water mains: physically based models. *Urban Water Journal*, 3, 151-164.

Renaud, E., Le Gat, Y. and Poulton, M., 2012. Using a break prediction model for drinking water networks asset management: From research to practice. *Water Science and Technology: Water Supply*, 12.5, 674-682.

Rostum, J., 2000. *Statistical Modelling of Pipe Failures in Water Networks*. Norwegian University of Science and Technology, Department of Hydraulic and Environmental Engineering, PhD thesis, Trondheim, Norway, 132p.

Shamir, U. and Howard., C., 1979. An analytic approach to scheduling pipe replacement. *Journal of American Water Works Association*, 71, 248-258.

Scholten, L., 2013. *Multi-criteria decision analysis for water supply infrastructure planning under uncertainty*. PhD thesis ETH Zurich, Switzerland, 293.

Taillandier, F., 2009. *La notion de risque comme clef du pilotage d'un parc patrimonial immobilier*. PhD thesis, Universite de Savoie, specialite : genie civil, France, 331.

Ugarelli, R. and Bruaset, S., 2010. *Review of deterioration modelling approach for ageing infrastructure*. SINTEF, 40.

UKWIR, 2009. *Factors Affecting the Natural Rate of Rise of Leakage*. 09/WM/08/40, UKWIR (United Kingdom Water Industry Research).

Viscor, P., 1997. *Spolehlivost vodovonich siti*. PhD thesis, University of Technology, Brno, Czech Republic.

Vitorino, D., Coelho, S. T., Alegre, H., Martins, A., Leitao, J. P. and Silva, M. S., 2012. *Aware-P software documentation*. 38.

Walski, T. M. and Pelliccia, A. 1982. A. Economic analysis of water main breaks. *Journal of American Water Works Association*, 74, 140-147.