

WATERLOSS MODELLING FOR URBAN WATER DISTRIBUTION NETWORKS

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ABSTRACT

Control of water losses associated with inefficiencies of the underground water distribution system is very important for all countries with arid climate conditions and shortage of water supplies, because they are causing not only revenue losses for the local Water Boards but most importantly they negatively affect the national water reserves. Presented herein is an integrated mathematical model for the management of water distribution networks based on data from two different water distribution networks, spanning a period of about 10 years. The proposed methodology focuses on the sustainable management of water piping networks through the development of a mathematical model which aims the creation of a multiparameter decision system based on artificial neural networks and fuzzy logic. The goal is to enable the field engineers and maintenance technicians of water utilities to better manage condition assessment information, to process historical records with a number of analytical and numerical models, to identify underlying data patterns with artificial intelligence techniques and eventually to assess the corresponding risk of failure of each network element. Such management strategies should assist the network owners evaluate the condition of their network, assess historical incident and risk of failure data and prioritize the work based on the inherent risk and cost of action.

1 INTRODUCTION

The uninterrupted water supply, reduction of network damages, efficient use of water resources and effective management of urban water distribution networks (UWDN) are the ultimate goals for every organization which is in charge of such networks. Currently, a variety of water distribution network management techniques is available for use by the water boards. These techniques may either be in a format of guidance notes by the water associations (Farley, 2001; Hunaidi, 2000; Lahlou, 2001; Morrison et al., 2007) or service packages by consultant companies or autonomous tools emanating from research products (Hunaidi and Giamou, 1998; Lee and Tsuda, 2005; Pilcher et al., 2007). The majority of such management techniques are related with the measures taken by the network managers to detect network leakages as soon as possible and conversely with their actions for restoring the networks to the previous operating condition. There also exist several techniques which are used for leakage prevention

through supervision of the UWDN and the use of robotic cameras for inspecting water pipes. The two main disadvantages of the techniques mentioned above are: (1) they do not prioritize simultaneous leakage incidents and, (2) the resulting precaution measures are not based on each specific network's topology but, rather, they are activated periodically across the network. Presented herein is a proactive management strategy that assists the network owners evaluate the condition of their network, assess historical incident and risk of failure data and prioritize the work based on the inherent risk and cost of action. The goal is to enable the field engineers and maintenance technicians of water utilities to better manage the collected condition assessment information, to process historical records with a number of analytical and numerical models, to identify underlying data patterns with artificial intelligence techniques and eventually to assess the corresponding risk of failure of each network element. Therefore, UWDN engineers will be able to prepare a proactive organized service plan for their distribution network. Furthermore this model can be used by the network managers as a tool in cases where they have to: (1) decide the replacement or repair of a deteriorating network part and (2) prioritize simultaneous leakage incidents. This, in turn, helps them to manage their networks in a more efficient way so they can minimize their operational and maintenance costs.

The effort is part of a research project funded by the Cyprus Research Promotion Foundation (under Grant No. PENEK/0308/34) and the European structural funds, titled "Urban Water Distribution Modelling, Simulation and Optimization of Leakage Detection Via Sensing Technologies (UWDM)", having at its core not only the aforementioned analytical tools but also the utilization and integration of wireless sensor networks for the processing of information on operational characteristics of the network.

2 STATE OF KNOWLEDGE

Research related with water distribution networks modelling has concluded that a number of risk factors, some time-dependent and some time-invariant, are contributing to pipe failures. The centre of attention for the most of such research activities was placed to the determination and expansion of the relation between pipe failures and the factors related with it. The main risk factors reported by the various researches are the age, diameter and material of the water pipe, the historical data of previous breaks (Number of Previous Breaks; NOPB), the network's operating pressure, the underground temperature variance and the external loading.

Some studies tried to develop a single-objective mathematical model expressing the failure pattern or system reliability whereas other researches expanded further by presenting multi-objective failure models. Shamir and Howard (1979) and Clark et al. (1982) using different approaches developed mathematical relationships which express the time from pipe installation until the first failure incident and the failure frequencies after the first one occurred. Andreou et al. (1987) used proportional hazards models to estimate failure at an early age and a Poisson-type model for the later stages. Also Goulter and Kazemi (1988) presented a non-homogeneous Poisson distribution model which predicts the probability of successive breaks after the first failure occurred. A multi-objective generic algorithm measure, which tried to provide surplus head above the minimum allowable head at nodes and reliable loops with practicable pipe diameters, was proposed by Prasad et al. (2003). Fattahi and Fayyaz (2009) developed a multi-objective model having as variables the water distribution cost, the leakage water

and the social satisfaction level. The mathematical model was used for optimizing the urban water management. Kanakoudis and Tolikas (2004) suggested a management system that estimates the performance level of a distribution network if a new action is being taken on it. The proposed model takes into consideration the repair and replacement costs of failing pipes.

Recent researches have moved a step further by developing models which simulate UWDN behaviour and include decision support systems for the network managers. Christodoulou et al. (2007) and Christodoulou et al. (2010) developed a framework for integrated GIS-based management, risk assessment and prioritization of water leakage actions. Tuhovcak et al. (2006) applied the Hazard Analysis and Critical Control Points methods for the risk analysis of UWDN. Finally, Park (2008) proposed a proportional hazard model which estimates and then tracks changes of the hazard function of the various pipe types in an UWDN between the observed water main failures.

3 MATHEMATICAL MODEL

Survival Analysis was chosen as the modelling method to describe and simulate the time-related risk-of-failure relationships in UWDN. Survival analysis is a branch of statistics dealing with deterioration and failure over time. It involves the modelling of the elapsed time between an initiating event and a terminal event (Klein and Moeschberger, 1997; Hintze, 2006). For this case, where water distribution networks are involved, initiating event is represented by the date of pipe installation, near terminal event is represented by the date of pipe repair and terminal event is represented by the date of a pipe replacement. The mathematical model estimates the reliability of a system and its lifetime, subject to multiple risk factors. It aims to analyse the effect of the various risk factors on the system's lifetime and the probability of survival, and the expected mean time to failure of each individual part of the system (Lee and Wang, 2003; Hintze, 2006). The data values used in the analysis are a mixture of complete and censored observations.

3.1 Kaplan–Meier estimator

The proposed mathematical model estimates the survival function by use of nonparametric Kaplan–Meier estimator (Kaplan and Meier, 1958) (Eq. 1),

$$\hat{S}(t) = \begin{cases} 1 & \text{if } T_{\min} > T \\ \prod_{A \leq T_i \leq T} \left[1 - \frac{d_i}{r_i} \right] & \text{if } T_{\min} \leq T \end{cases} \quad (1)$$

where d_i is the number of failures occurring in time T_i (D_i is the set of these failures); r_i is the number of the individuals that are at risk immediately before time T_i (R_i is the set of all individuals that are at risk immediately before time T_i); T_i is the termination time (failure event) for the i^{th} event; and A is the minimum time considered below which failures are not considered (that is the case when data is left-truncated).

A Kaplan–Meier plot, estimate of the survival function, is a series of horizontal steps of declining magnitude which approaches the true survival function for that population (A large enough sample is needed). The value of the survival function

between successive different sampled observations is assumed to be constant. One of the advantages of the Kaplan–Meier estimator is that it can take into account missing data, thus being able to approximate the underlying probability distribution function even in the presence of incomplete datasets (Klein and Moeschberger, 1997).

3.2 Hazard Ratio

The hazard rate (or conditional failure rate) is a metric which is usually used for identifying the appropriate probability distribution of a particular mechanism (Hintze, 2006). During survival analysis is very useful to compare the hazard rates of two groups of similar attributes within the examined dataset, by employing the hazard ratio (HR). HR is a metric that estimates the relative risk of an event. The hazard ratio of two data sets with covariate values of x_0 and x_1 is given by:

$$HR(t, x_1, x_0) = \frac{h(t, x_1, \beta)}{h(t, x_0, \beta)} = \frac{h_0(t) r(x_1, \beta)}{h_0(t) r(x_0, \beta)} = \frac{r(x_1, \beta)}{r(x_0, \beta)} \quad (2)$$

Equation 2 shows that the hazard ratio depends only on the function used to model failure. This property allows the comparative examination of the risk factors and their effects on the survivability of the subject in examination. In this case, compare the risk factors that influence the failure of the water pipes within a distribution network.

4 ANALYSIS AND RESULTS

The work presented herein is based on operating data from Water Board of Nicosia, Cyprus (NWB).

4.1 Case study – Nicosia Water Board

The NWB was established in 1951 and became operational in 1953. The NWB network covers the largest municipalities of Nicosia district. Additionally, after a Government decision, the NWB provides water in the area of Nicosia which is currently under the control of the Turkish military. According to 2007 data, the NWB network requires about 19,400,000 m³ of water per year in continuous flow, while the maximum daily demand in summer is around 59,200 m³. The minimum consumption per day is 47,200 m³, while the daily average water consumption is 53,000 m³. The needs in water are covered partially by the Dekelia and Larnaca water desalination plants and partially by the Kouris and Dipotamos dams. The NWB has in operation about 103,000 water meters, a number which corresponds to more than 1/3 of the total population of Cyprus. The total length of network mains is more than 1200 km and the network's water tanks have a total capacity of approximately 75,000 m³ of water. For better control and network management a remote control system (SCADA) was installed and is currently operated, consisting of 32 electronic stations across the network. These stations collect and transmit operational information about the flow and pressure of specified points in the network so that the system managers can take the right decisions in managing the network. Furthermore, in order to better manage it, the NWB has divided the network been into 60 District Metered Areas (DMAs) and Sub-DMAs. Finally, apart FROM the SCADA telemetry system database, the NWB has computerized all the leakage incident data reports since 2003.

4.2 Data Analysis

The data analysis presented in this study was developed using the NWB data for the period 2007-2010. The aforementioned period is particularly interesting because during these years, and following an extended drought period of 3 years the island of Cyprus was faced with extreme water shortage which in turn necessitated an intermittent water supply policy. The goal of the analysis was to extend the models and analyses previously developed by Christodoulou (2011) and Christodoulou et al. (2010) as those were applied to UWDN under normal operating conditions and investigate the effects of intermittent water supply on the vulnerability of UWDN.

Since this analysis is based on a three-year period (2007-2010) and in the absence of information for the years between the “date of birth” and the “date of failure” for the pipes with observed breaks, the leak data was left-censored at 01/01/2007 and right-censored at 31/12/2010. Additionally, the “date of failure” and the “date of rebirth” were considered to be the date that a leak-related incident was reported. Another assumption dictated by the location-invariant data collected by NWB, is that the survival analysis was made by street and not by pipe segment. Finally, only leak-observed incidents related to pipes (water mains and/or house connections) were classified as breaks, while all other incidents (such as valve failures and/or manifold failures) were not.

The non-parametric Kaplan-Meier survival analysis estimator was used for the analysis and the data analysis results are presented by the survival and hazard rate plots given below (Figures 1 and 2 respectively).

Figure 1 represents the survival plot for both the house connection pipes and the water mains. It can be seen from the survival curves that the behaviour of the two different pipe classes very similar with a slightly better performance by the house connection pipes. Also water mains have slightly faster drop in survival rate at the beginning while house connection have faster drop at the end. Notable is the change in the curves' slopes at about $t=285$ and the increased pace in the reduction of survivability. As previously mentioned, the period from March 2008 to January 2010 was the period when intermittent water supply policies were in effect, and during this period the failure incidents dramatically increased. Also, during this period, the increase of house connection incidents was proportionally higher than the corresponding number water main breaks, explaining its fast drop at the end of the plot. The curves reinforce the observation that the intermittent supply policies had a negative effect on the survivability of the pipes.

Figure 2 depicts the hazard rate plot for the studied period. As in the case of the survival plot the curves show an almost identical behaviour by the two pipe classes. The water mains curve has slower hazard rate than the curve for the house connections, despite the fact that initially it has a higher hazard rate. The hazard rate slope for the water mains is 0.105/300 days (i.e. ~ 0.00035) whereas the slope for the house connections is 0.185/300 days (i.e. ~ 0.00062), thus indicating that house connections were affected the most by the intermittent water supply policy.

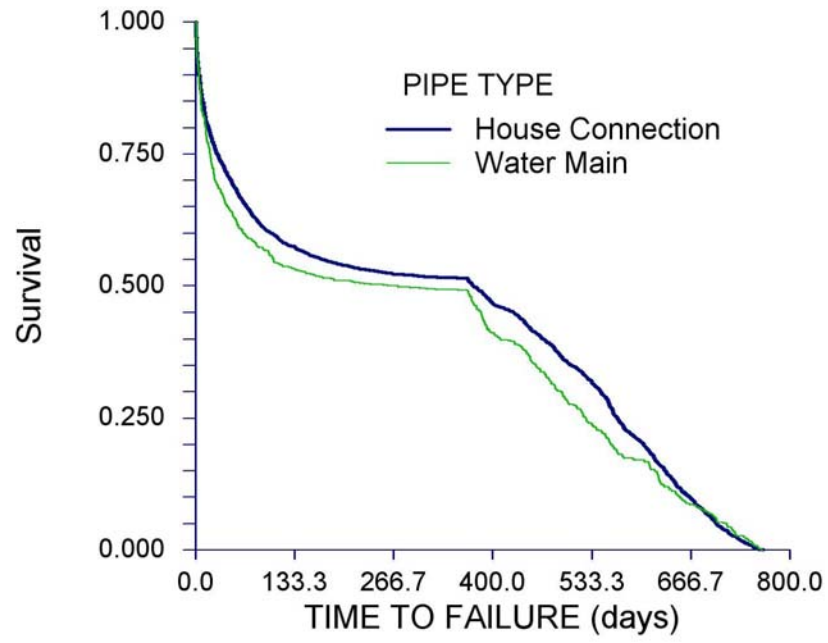


Figure 1. Survival Plot.

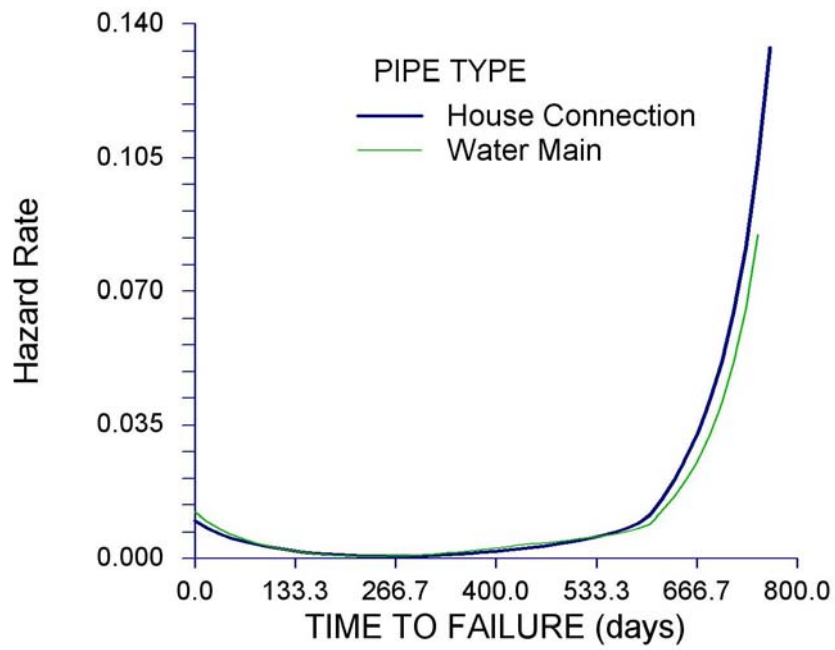


Figure 2. Hazard Rate Plot.

5 CONCLUSIONS

The manuscript outlines a method for evaluating the performance of UWDN. The ultimate scope was to enable field engineers and maintenance technicians of water utilities to better manage condition assessment information and to identify underlying data patterns to eventually be able to assess the corresponding risk of failure for each network element.

Survival analysis results for a period of three years show that the behaviour of two principle UWDN component classes (water mains and house connection pipes) are almost identical over time under normal operating conditions. However under abnormal operating conditions (such as in the case of intermitted water supply) the survival curves show that for the specific UWDN the house connections are more vulnerable and at almost double the hazard rate compared to water mains.

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