

URBAN WATER DISTRIBUTION NETWORK PERFORMANCE UNDER INTERMITTENT WATER SUPPLY CONDITIONS

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ABSTRACT

The work presented herein investigates the effects of intermittent supply on the performance and fragility of urban water distribution piping networks (UWDN), examining the resulting water losses, the inefficiencies and the overall maintenance cost on these networks during extreme operating conditions such as intermittent water supply. The analysis, based on a six-year dataset (2003-2010), shows an increase in the number of water-leak incidents during and immediately after the years of enacting intermittent water supply policies, and it reinforces the belief that intermittent supply has several adverse effects and increases the vulnerability of UWDNs.

1 INTRODUCTION

Faced with extended periods of drought and in short supply of water, Cyprus had in recent years turned to enforcing intermittent water supply as a measure to curb consumer demand and to prolong the country's national water reserves. The measure, even though extreme and unthinkable in many other countries around the globe, was deemed a must by the Cyprus' national and local authorities as the extended drought engulfing the island coupled with an observed desertification and a heightened tourism-related demand for water, brought the water reserves to a dangerous low and the island to its knees.

The measure for intermittent supply was enacted nationwide in April 2008 and eventually ended in mid 2010, upon the successful accelerated construction of additional desalination and wastewater treatment plants that significantly increased the volume of available/usable water. Noteworthy is also the fact that during the same period and in wait of the new water plants to come online, the national authorities had gone through the extreme measure of importing water from a neighbouring country by use of tankers (2008-2009).

2 SCOPE OF WORK

The intermittent water supply lasted for about 2 years (Mar. 2008 – Oct. 2010) and was presumed to have reduced the overall water consumption on the island by about 20% (by volume of water) compared to previous years. This savings estimate, even though calculated based on the total water consumed, was actually the direct result of the reduction in the water supplied by the Republic's Water Development Department. In effect, the water entering the UWDN from the water dams/reservoirs was about 20%-30% less than the volume of water supplied to the networks under normal operating conditions. Thus the presumed savings were simply supply-driven and not demand-driven. Furthermore, the presumed water savings did not take into consideration the side-effects of the intermittent water supply policy on the piping networks and the resulting water loss thereafter.

The work presented herein investigates the effects of intermittent supply on the performance of the underlying urban water distribution piping networks (UWDN) and on the fragility of such networks, examining the resulting water losses, inefficiencies and overall maintenance cost on these networks during such extreme operating conditions. The analysis is based on a seven-year dataset (2003-2010) from the largest two urban locales on the island, and it includes information on breakage incidents, operating network parameters, external factors (such as the prevailing weather conditions) and vulnerability assessments.

A variety of data-mining and survival analysis techniques are employed in examining the aforementioned factors and in evaluating the effects of such intermittent supply strategies on the vulnerability of the water pipes and on the sustainability of the strategy. Preliminary analysis results show an increase in the number of water-leak incidents of approximately 28% during the year of enacting the intermittent water supply policies. Data stratifications of the type, the material and diameter of each pipe, the seasonal weather, the soil conditions and the water pressure levels at the time of each water-leak incident are also in progress, shedding light to the behaviour of the piping network under the aforementioned adverse operating conditions.

3 PAST RESEARCH WORK

To-date a number of studies on infrastructure assessment and deterioration modelling of urban water distribution networks (UWDN) have been undertaken. The intent of such studies has traditionally been to assist UWDN operators in improving their understanding of the network's behaviour over time, its deterioration rate and its reliability with respect to presumed risk factors. One of the principal research goals has been the devising of "repair-or-replace" decisions for UWDN based on sound scientific reasoning via statistics, risk analysis and decision support systems. In most cases, past studies attempted to identify the causal relationships between UWDN pipe breaks and presumed risk factors such as a pipe's age, diameter and material, the corrosiveness of the soil, the operating pressure and temperature in the network, previously observed breaks and the various external loads.

In brief, most studies in literature show a relationship between failure rates and time of failure (age of pipes) and some of them suggest a methodology to optimize the replacement time of pipes. For example, Shamir and Howard (1979) reported an

exponential relationship. Clark (1982) developed a linear multivariate equation to characterize the time from pipe installation to the first break and a multivariate exponential equation to determine the breakage rate after the first break. A study by Andreou et al. (1987) suggested a probabilistic approach consisting of a proportional hazards model to predict failure at an early age, and a Poisson-type model for the later stages, and further asserted that stratification of data (based on specific parameters) would increase the accuracy of the model. A non-homogeneous Poisson distribution model was later proposed by Goulter and Kazemi (1987) to predict the probability of subsequent breaks given that at least one break had already occurred. Finally, Kleiner et al. (1998, 1999) developed a framework to assess future rehabilitation needs using limited and incomplete data on pipe conditions. Finally, Christodoulou et al. (2006, 2009, 2010a, 2010b) reported on the development of decision-support systems (DSS) integrating GIS-based management, risk assessment and prioritization of water leakage actions. Their work was later supplemented with Survival Analysis for modelling the deterioration of UWDN components over time (Christodoulou 2011).

Unfortunately very little, if anything, has been reported in literature with regards to UWDN modelling under abnormal operating conditions such as the condition related to intermittent water supply. This aspect of UWDN modelling is the subject of this research work, with some preliminary findings reported herein.

4 INTERMITTENT WATER SUPPLY AND ITS EFFECT ON UWDN

4.1 The Case-Study UWDN

The UWDN in study has been the centre of several related studies in the past and documented in literature (Christodoulou et al., 2006, 2009, 2010a, 2010b, 2011). The UWDN currently under review (Water Board of Lemesos) is over 50 years of age and serves approximately 170,000 residents through approximately 64,000 consumer meters in an area of 70 km². The annual volume of potable water distributed through the network of pipes, of approximate length 795 km, is about 13.7×10⁶ m³ and of value €7.0 million.

4.2 Pre-Enactment Period

As aforementioned, previous studies by Christodoulou et al. (2009, 2010b, 2011) have reported on the effect of several potential risk factors on the fragility and the probability of failure of UWDN pipes. Those studies initially identified as most influential risk-of-failure factors to be the number of previously observed breaks (NOPB), the material type (MAT), the length (L) and the diameter (D) of each pipe (Christodoulou et al., 2006), and then deduced rules about the relative importance of such factors. The deduced knowledge was based on specific datasets and several analytical or artificial intelligence techniques such as pattern recognition, neurofuzzy systems and data-mining methods.

For example, Christodoulou et al. (2010a) report that by using several data stratifications on a Lemesos dataset spanning a 5-year period (2002–2007) and about 2,000 break incidents, they were able to deduce that:

- *“Data stratification based on the pipes’ material type reveals that the hazard rate of the black-color medium density polyethylene (MDPE) pipes is higher*

than galvanized (GI), asbestos cement (AC) and MDPE-blue pipes... The deviation in hazard rate between the various material types is about 0.0004 at the lower end of the pipes' life expectancy (~11,000 days, ~30 years) and increases to about 0.0032 at the upper end of the pipes' life expectancy (~12,800 days, ~35 years)."

- "Data stratification based on the type of incidents producing pipe bursts reveals that the hazard rate related to pipe deterioration greatly outpaces the hazard rate of the other incident types (corrosion, interference by others, tree roots, connection hose, other). What starts as a relatively small deviation at the start of the observed failure time (at about 30 years) soon doubles (0.008 vs. 0.004) at the upper end of the expected lifetime (at $t \sim 35$ years). And while the hazard rate for incidents attributed to tree roots, corrosion, connection hose or other reasons increases almost uniformly over time, the deterioration-related hazard rate accelerates over time (from 0.001 to 0.008). This is an indication that aging pipes should be replaced at smaller time-intervals (at about 11,000 days ~ 30 years), otherwise the risk of failure increases substantially."
- "Also of interest is the observation that the hazard rate related to corrosion accelerates in time and surpasses the rate of increase of interference-related, tree-roots and connection-hose incidents. Similarly, incidents related to the existence of tree roots in the vicinity of pipes and their effect on pipe failure have a hazard rate which is accelerating over time. This is an indication that pipes in the vicinity of trees should be monitored more closely and/or replaced in smaller time intervals than other pipes."
- "Finally, data stratification based on the pipe diameter reveals that medium and large diameter pipes have approximately the same hazard rate over time but small-diameter pipes have an increasing hazard rate. This is an indication that small-diameter pipes should be replaced at smaller time intervals than medium and large-diameter pipes. The observation may be attributed to the fact that the pipe network in study consists primarily of small-diameter pipes (neighbourhood and house connection pipes) that operate under relatively high pressures and therefore are subject to increased risk of failure."

Also documented, in Christodoulou and Deligianni (2010b), is the criticality of the "number of previously observed breaks (NOPB)" risk factor. The hazard rate for the NOPB factor was subsequently shown to be a dominating parameter, especially for the range of $4 \leq \text{NOPB} \leq 8$, wherein if NOPB is increased by 1 incident then the hazard rate increases by 20.49%. Thus, a pipe with, let's say 5 previously observed breaks is 20.49% more likely to fail than a pipe with 4 breaks, and 41% more than a pipe with 3 breaks.

4.3 Post-Enactment Period

As previously stated, the intermittent supply policy lasted for about 2 years (Mar. 2008 – Oct. 2010). However, the dataset analyzed covers a more extended period (2007-Jan.2011) and includes 11,354 incidents of which 9,034 occurred during the intermittent supply period (2008-2010).

During the intermittent supply policy's first year alone, the Water Board of Lemesos reported a total of more than 2,500 service calls related to water-loss or pipe-inspection incidents. The number of incidents has since then risen to about 10 per day. Notable is the case of Nicosia's UWDN, which for the same period shows about 70-80 incidents per day; a number that is disturbingly high. The majority of these incidents were related to house connections and small-diameter pipes, with an increase in the corresponding incidents during the intermittent supply period of about 135% compared to the normal operating conditions period (uninterrupted supply). This finding is in agreement with the fourth finding of the analysis by Christodoulou et al. (2010a) on the increased risk of failure of house-connection pipes.

As Table 1 shows, the total number of incidents per annum increased from 2,092 in 2007 (the presumed steady state condition) to 2,565 in 2008, 2,853 in 2009 and 3,566 in 2010. This, compared to the steady state condition (year 2007), translates to an increase of 23% for 2008, 36% for 2009 and 70% for 2010. The numbers are again alarmingly high. Table 1 also shows an increase in the incidents on water mains of about 158% in year 2010 compared to the base year of 2007 (2,603 vs. 1,010). A similar situation is observed on the incidents pertaining to house connections (71% increase, 598 vs. 350 incidents). The intermittent supply policy seems to have burdened the UWDN with additional "loads" and increased the risk of failure for its piping components (Figure 1).

Table 1. Annual number of pipe-related incidents (Lemesos dataset).

Incident Type	2007	2008	2009	2010	2011	Total
Leak (water main)	1,010	1,497	2,328	2,603	201	7,639
Leak (house connection)	350	334	270	598	44	1,596
Apparent water leak	164	3	2	32	10	211
Faulty water meter	2	2	2	-	-	6
No water	83	93	92	118	12	398
Water waste	428	345	89	109	4	975
Low water pressure	48	37	55	103	5	248
Miscellaneous	7	254	15	3	2	281
Total	2,092	2,565	2,853	3,566	278	11,354

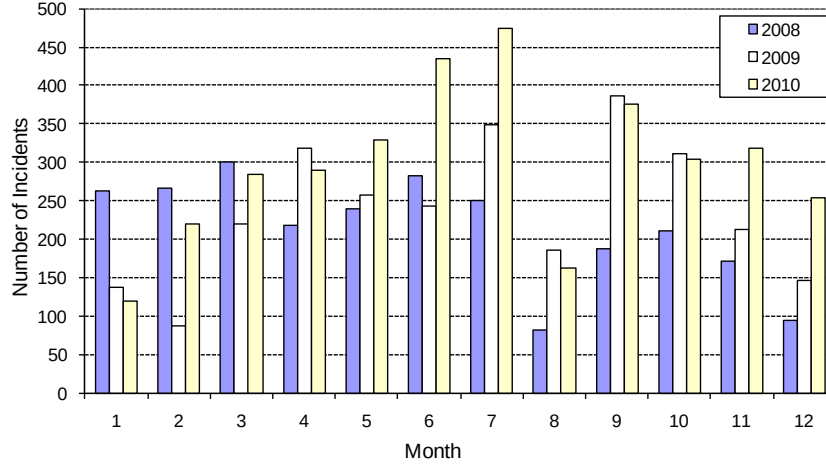


Figure 1. Incidents per month, for three-year period of intermittent supply (Lemesos dataset).

5 SURVIVAL ANALYSIS

The statistical analysis was supplemented with survival analysis modelling of the time-to-failure (TTF) metric for the aforementioned two basic pipe classes (“water mains” and “house connection pipes”). Survival analysis is a powerful method for modelling the behaviour of a component over time, especially in the presence of incomplete time data. In this case a non-parametric survival estimator was used (the Kaplan-Meier estimator), as given by Eq. 1 (Hintze 2006).

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

The survival analysis used the aforementioned 4-year dataset (2007-2010) and water-loss incident information on the date/time of event, the location (street), the type of pipe (diameter, material), the type of pipe (house connection, water main) and the number of previously observed breaks. Furthermore, the method allowed for incomplete data through the incorporation of left-censored and right-censored time flags. The results of the analysis are captured in Figures 2 and 3.

Figure 2, showing the survival of water mains and of house connection pipes, indicates an almost identical behaviour over time for these two piping classes. A closer look at Figure 3, though, indicates a faster hazard rate (for $t > 1125$ days) for water mains compared to house connections. This, in effect, translates to a higher vulnerability for water mains.

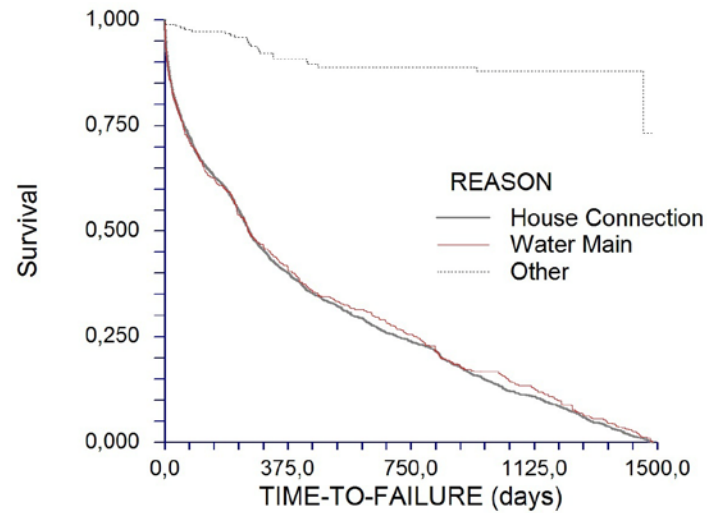


Figure 2. Survival plot, clustered by pipe type (Lemesos dataset).

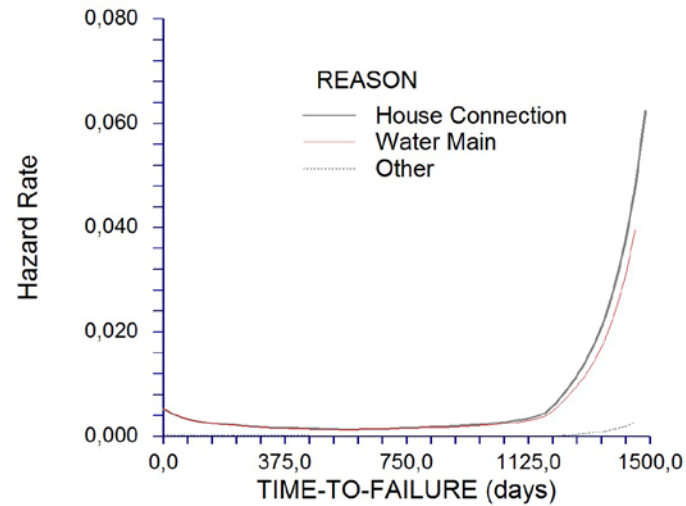


Figure 3. Hazard rate plot, clustered by pipe type (Lemesos dataset).

Similarly, a plot of the hazard rate based on clustering by material indicates that MDPE (black) type are the most vulnerable to the abnormal operating conditions in the network, exhibiting steeper hazard rates compared to the other pipe types. This is in agreement with the results from previous studies by Christodoulou et al. (2010a).

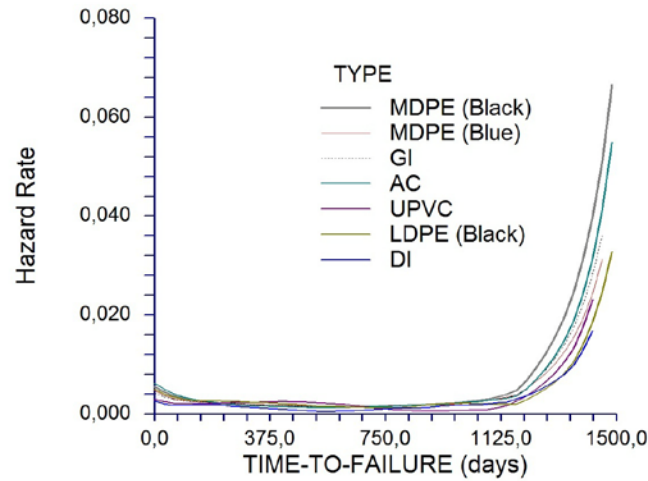


Figure 4. Hazard rate plot, clustered by pipe material (Lemesos dataset).

Furthermore, the analysis shows that the hazard rate of the MDPE (Blue) pipes has also picked up pace ranking MDPE (Blue) second in vulnerability (Figure 4). Galvanized (GI) and asbestos cement (AC) pipes are ranked third and fourth in vulnerability. In effect, the intermittent supply policy seems to have increased the risk of failure for MDPE (Blue) pipes. The same conclusion can be reached for pipes exhibiting a high number of previously observed breaks (NOPB). As Figure 5 shows, the pipes in the clusters “NOPB medium” and “NOPB large” have a rapidly decreasing survival curve as compared to the pipes belonging to the “NOPB small” cluster. This translates to a higher vulnerability and shorter life spans for these pipes.

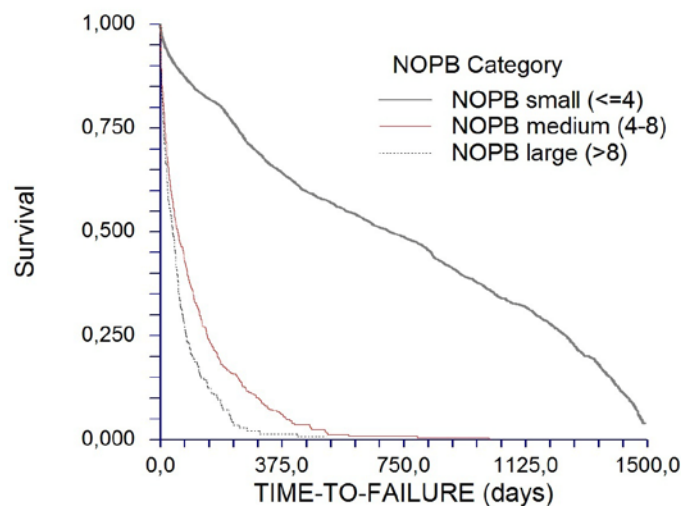


Figure 5. Survival analysis plot, clustered by NOPB class (Lemesos dataset).

6 CONCLUSIONS

The manuscript presents preliminary results of a study on the effects of intermittent supply on the reliability of an urban water distribution network. The study spans a 4-year period (2007-2010) and includes about 20,000 water-loss incidents from two metropolitan water distribution networks in Cyprus in which intermittent supply policies were enforced during the period 2008-2010.

The results show a dramatic increase in pipe-burst incidents that can be attributed directly to the intermittent supply policy. This increase is especially evident in deteriorating pipes (with NODB 4) and small -diameter pipes (primarily house connections). Even though it is understood that the primary reason for enacting an intermittent-supply policy is to reduce water consumption as forced upon us by extreme drought conditions, the post-policy analysis indicates that side-effects of such policy are equally significant and worthy of consideration. Such side-effects are the increase in pipe-burst incidents, the increased water loss due to intermittent-supply induced leaks in the network and the increased cost for maintaining the networks under such abnormal operating conditions.

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