Rehabilitation and maintenance of water distribution network assets

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ABSTRACT

In light of the increasing and pressing need to efficiently manage scarce water resources, there has been renewed interest by water distribution network owners to develop and implement water management strategies and tools that would assist in the integrated and automated management of those networks. Such asset management strategies should assist the network owners to evaluate the condition of the water distribution network, assess historical incident data (leakage or breakage) and risk of failure, visualise areas of high risk, propose "repair or replace" strategies and prioritise the work based on the inherent risk and cost of action. The methodology and support system outlined in this paper can form an integral part of a leakage management strategy and provide a useful decision-making tool. The work presented outlines an integrated methodology and a decision support system for arriving at such "repair-or-replace" decisions, as part of a long-term pipeline asset management program that could be undertaken by a water utility to improve on the reliability of the water distribution networks.

Key words | asset management, repair or replace, risk of failure

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INTRODUCTION

Increased demands on resource usage, reliability of systems and of provided services placed on urban utility owners as a direct result of the ongoing globalisation and urbanisation have put a high strain on ageing urban infrastructure and water distribution agencies.

This is even more evident and time-pressing in countries with limited water resources. In such cases, the complexity and severity of the problem is compounded and amplified by the inability of the owners of the distribution network to easily and cost-effectively replace utilised or lost resources (water and pipes) as they are faced with a lack of alternatives and a pressing need to provide these resources to the public in periods of extended drought. After all, in the case of water distribution networks the resource managed and provided to customers (water) is the essential element for life and no substitute can fulfill this resource's role. Furthermore, in the case of most developing countries the managed distribution networks are based on ageing and neglected infrastructure that is highly unreliable and cost-inefficient. As a result, utilities in charge of managing such water distribution networks are nowadays faced with the increasingly more complex task to intelligently and efficiently manage such networks in ways that maximise a system's reliability and minimise its operational and management costs. In these cases, life-cycle costing and maintenance strategies become of paramount importance to the utilities as they seek ways to increase system reliability and quality of service while minimising costs of operation.

Central to this balancing act of operating costs and reliability is one of the most important dilemmas facing water distribution-organisations. Should an organisation repair or replace ageing and/or deteriorating water mains and what, in any case, should the sequence of any such repairs be as part of a long-term network rehabilitation strategy?

The work presented outlines an integrated methodology and a decision support system for arriving at such

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"rehabilitate-or-replace" decisions, as part of a long-term pipeline asset management program that could be undertaken by a water utility to improve on the reliability of the water distribution networks. The International Water Association's Water Loss Task Force has been advocating and promoting four basic leakage management activities for leakage reduction, namely: pressure management, active leakage control, speed and quality of repairs and pipeline asset management, maintenance and renewal (Lambert & Mckenzie 2002). The methodology and support system outlined in this paper can form an integral part of a leakage management strategy and provide a useful decision-making tool.

Relevant studies in literature

To date, a number of studies has been undertaken on infrastructure assessment and deterioration modelling; with the intent of assisting owners of such systems to improve their understanding of a system's behaviour over time, its deterioration rate and its reliability with respect to presumed risk factors. The intent has always been to assist owners and operators of water distribution networks in arriving at "repair-or-replace" decisions on a more scientific basis. The studies usually attempt to identify statistical relationships between water main break rates and influential risk factors such as a pipe's age, diameter and material, the corrosiveness of the soil, the operating pressure and temperature, possible external loads (including highway traffic) and recorded history of pipe breaks.

Most studies in the literature show a relationship between failure rates and time of failure (age of pipes), and some of them suggest a methodology to optimise the replacement time of pipes. Shamir & Howard (1979) reported an exponential relationship, and Clark *et al.* (1982) developed a linear multivariate equation to characterise 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 & Kazemi (1988) to predict the probability of subsequent breaks given that at least one break had already occurred. Finally, Kleiner *et al.* (1998) and Kleiner & Rajani (1999) developed a framework to assess future rehabilitation needs using limited and incomplete data on pipe conditions. More recently, a simulation model was applied to an inventory of water mains in New York City to analyse replacement strategies, and Vanrenterghem (2003) developed models for the structural degradation of urban water distribution systems based on data from New York City. Additional work on the same case study was reported by Aslani (2003) and Christodoulou *et al.* (2003). The knowledge gained by the New York City case study was furthered and reported upon by Christodoulou *et al.* (2006) in a developed framework for integrated GIS-based management, risk assessment and prioritisation of water leakage actions.

Integrated water leakage management system – a case study

In managing water distribution assets (water, pipes, valves, connections, etc.) water utility agencies need to implement asset management strategies, alongside operations and maintenance methodologies, that improve on a system's reliability and cost-efficiency. To that effect, an integrated pipeline asset management system is of high importance. The system proposed in the following pages is an example of such a system as developed and implemented in Cyprus for the monitoring, rehabilitation and life-cycle-costing of urban water distribution networks.

The described integrated system and the lessons learned from its implementation are in essence a knowledge-based system, complemented with analytical and numerical analysis tools and supplemented with a geographical information system (GIS) for the delivery to water distribution network owners and administrators of a complete decision support system (DSS) that can help them improve on the management of the water distribution networks.

The proposed integrated pipeline asset management system

Starting with the premise that historical data on pipe breaks, reaction methodologies, social and financial impacts and life-cycle costing are important ingredients in the puzzle of "repair or replace" strategies and action prioritisation, the proposed system envisions the integration of all these key elements in the delivery of one integrated management system which will help utilities manage their distribution networks more efficiently.

As such, the proposed system encompasses:

- data on system characteristics (such as pipe diameter, length, material, installation date, zoning, etc.);
- historical data on pipe break incidents (date of incident, response time and cost to repair/replace, number of previously observed breaks, reason for and classification of break incident, etc.);
- a statistical analysis tool for the analysis of pipe break incidents;
- an artificial neural network component for data pattern identification;
- a fuzzy logic processor, for the development of fuzzy logic rules describing the behaviour of the network;
- a risk assessment module (primarily a survival analysis module);
- a geographical information system (GIS) for visualisation;
- a life cycle costing module for the aggregation of costs by area and pipe;
- a prioritisation-of-work module;
- a data query and reporting system for the retrieval of needed information.

System's process and data flow

The system proposed relies heavily on past knowledge acquired through operations and maintenance by the Water Boards, and historical records relating incidents on the network (primarily pipe failures) with internal and external parameters. Sample internal parameters include pipe materials, diameters, operating pressures, etc., and sample external parameters include external loading conditions, temperature, soil conditions, etc. The premise is that lessons learned through past incidents can significantly improve future operations and maintenance practices and thus improve the piping network's operational reliability and life-cycle costs. Furthermore, an integrated and automated methodology should help Water Boards more efficiently and intelligently address the "repair or replace" dilemma facing them, prioritise their actions and save on non-revenue water.

The proposed asset management, operations and maintenance system relies on a company access-wide relational database (client-server application) that feeds into a decision support system (DSS). This database comprises the time-related knowledge repository for the piping network, feeding related data to a neurofuzzy system which then processes the information to arrive at estimated risk-of-failure calculations. On the one hand, the underlying databases are relational and integrated to minimise entry points by the users, standardise input, minimise risk of errors in data handling, and maximise automation of data analysis and reporting. On the other hand, the DSS and its neurofuzzy elements allow for the numerical analysis of the data and the evaluation of key system parameters such as survival analysis curves and risk-of-failure metrics for each network element.

The latter (risk-of-failure metrics) is a key system characteristic of the piping network, for it provides the Water Boards with numerical appraisals on the condition of the city's pipe network. A high "risk of failure" index, or consecutively a low survival index, highlights to the Water Board a necessity to replace a failing pipe to avoid further escalation of the induced problem of repeated failures and downtime, as well as escalating operations and maintenance costs.

Historical data is processed by means of a combination of decision support tools, such as survival analysis, statistical analysis, artificial neural networks and fuzzy logic. This analysis aims to identify possible risk factors for pipe breaks and a ranking of them according to their severity and causal effect. Christodoulou *et al.* (2006) and Deligianni (2006) reported on the severity of a number of presumed factors (such as pipe diameter, material, length, age, number of previously observed breaks, etc.) and proceeded in listing the factors by means of a neurofuzzy system. A subset of the derived fuzzy rules is tabulated in Table 1.

The case-study water distribution network

The water distribution network currently under review (Water Board of Lemesos) is over 50 years of age and serves

Table 1 | Fuzzy logic rules describing expected behaviour of water pipes

If…					**Then…**
Diameter (D)	**Number of observed previous breaks (NOPB)**	**Length (L)**	**Material (Mat)**	**Traffic (Traf)**	**Break (1) or Not (0)**
Small	Small	Small	2	1	0
Small	Small	Small	1	1	1
Large	Large	Small	4	2	1
Medium	Small	Small	4	2	0
Small	Small	Medium	–	1	0
Small	Small	Large	1	0	0
Medium	Medium	Small	4	2	1
Large	Large	–	2	–	1
–	Small	–	1	–	0
S: 4–30″	*S: 0–2*	*S: 0.25–5.50*			
M: 20–48″	*M: 1–4*	*M: 4.50–14.0*			
L: 40–72″	*L: 3–9*	*L: 10.0–21.0*			

approximately 170,000 residents through approximately 64,000 consumer meters in an area of 70 km^2. The annual volume of potable water distributed through the network of pipes, of approximate length 795 km, is about $13.7 \times 106\,\mathrm{m}^3$ with a value of €7.0 million. The development of the system infrastructure took place in an extremely organised fashion with new areas of supply being incorporated into their respective pressure zones, which are strictly governed by contours. Each pressure zone is subdivided into district metered areas (DMAs), having a single metered source with physical discontinuity of the network between DMA boundaries. The DMAs vary in size from 50 properties to 7,000 (the average size being approximately 3,000 properties). Distribution main diameters within the DMAs vary between 100 and 250 mm and, where possible, interconnecting ring systems have been formed to minimise head loss at peak demands. The network owner has maintained records of its operational activities since 1963, which include production of water from sources, distribution through district meters and consumption from consumer meters. Meter readings at water sources (boreholes and treatment plant) are connected via a SCADA telemetry system to the control room. This enables continuous monitoring of the water source outputs and accurate recording of flows. Likewise, storage reservoir outlet meters are monitored on SCADA providing the same ability to observe trends as well as to record daily, weekly, monthly and yearly totals (Charalambous 2005). The continuous monitoring of the DMA metres combines information technology and telecommunication networks to transfer the data via the World Wide Web. The historical data gathered in the programmable controller of each DMA is sent by the controller to an email account. Operating software installed in the dedicated computer at the Water Board's control room connects to this email account twice a week and downloads the data, which are first sorted according to the DMA and then are used to update existing reports.

At a very early stage, the Water Board recognised the importance and significance of establishing a proper water audit system and has over the years developed its infrastructure in such a way so as to be able to account efficiently and accurately for all water produced or "lost" (non-revenue water). Reduction and control of water loss was achieved through the application of a holistic strategy based on the approach developed by the Water Loss Task Force of the International Water Association. An integral part of this approach is the establishment of a strategy for pipe break incidents ("pipe breaks policy"). The policy further envisions the prioritisation of the repair/replacement actions on the basis of risk of failure, life-cycle costing, social and financial impacts. In addition to the reported bursts, the Water Board of Lemesos, through its strategy for active leakage control, maintains records of unreported bursts located by means of acoustic leak localisers. Typical results are shown in Table 2 (Charalambous 2002). Details of all such breaks are maintained and included in the DSS analysis, together with the reported bursts.

Risk-of-failure analysis

Following the DMA strategy for minimising water losses through uniform pressure zones, the Water Boards recognised the need to develop mechanisms for evaluating historical incident data (when and how water pipes break) for identifying possible data patterns in the behaviour of the network, and for using these patterns for forecasting new breaks. The analysis of historical data was based on a number of analytical and numerical tools (such as statistical analysis, artificial neural networks, and neurofuzzy systems) and investigated the possible contribution of a number of presumed risk factors to a "Break or Not?" outcome, ranking these factors according to their relative importance and contribution to the "Break or Not" forecasted output. The analysis identified the most important risk 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).

The analysis on whether to repair or replace a burst, and thus the Board's asset management, is to be based on a combination of the previously mentioned tools (statistical analysis, survival analysis, neurofuzzy systems), with the end-results tabulated in a database management system and then mapped on a spatial database (GIS) that enables users to query both the raw data and the computed risk-of-failure values.

Table 2 | Unreported bursts–identified, located and repaired

	Number of bursts		Percentage per type	
Type of pipe	1999	2002	1999	2002
20 mm MDPE	7	7	39%	44%
32 mm MDPE	9	8		
100 mm AC mains	10	10	61%	56%
150 mm AC mains	12	9		
200 mm AC mains	3	0		
TOTAL	41	34	100%	100%
Estimated water saved	140,000 m^3	110,000 m^3		
Worth of water saved	US$ 45,000	US$ 35,000		

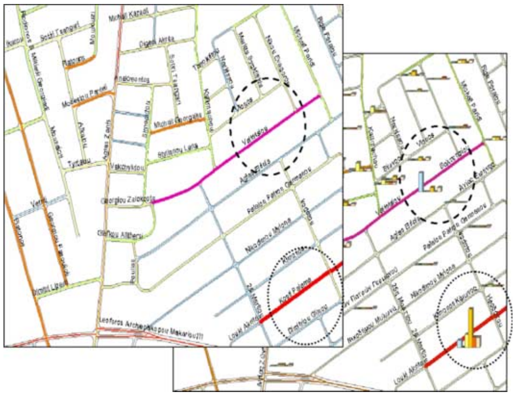

Figure 1 | Colour-coded GIS mapping of risk-of-failure. Subscribers to the online version of *Water Science and Technology:Water Supply* can access the colour version of this figure from http://www.iwaponline.com/ws.

Examples of the GIS-based decision support system are shown in Figures 2 and 3. At first, historical data on previously observed breaks (NOPB) are lumped at a street level and then mapped to a GIS representation of the pipe network, colour-coded to indicate the variable degrees of their inherent risk of failure (Figure 1). The Boards can therefore easily and holistically review the status of their network in terms of where and how often pipes break, as well as the computed risk-of-failure for each segment of the pipe network. Even though the eventual goal is to calculate risk-of-failure metrics at the pipe level and not the street level (in other words an individual forecast for each pipe segment) it was deemed redundant and over-complicating at this early stage of the research and thus overlooked in favour of metrics for each street segment.

The data is also categorised by the type of pipe for which burst incidents are reported, and is also graphed in histograms at the street level (Figure 1). For example, for two case-study streets (Valtetsiou and Kosti Palama) the histograms indicate the majority of incidents are AC and LDPE pipes, respectively. Should one break the data further down, the data can be categorised by pipe type (mains or house connections) or incident type (connection failure, corrosion, tree roots, deterioration due to aging) as shown in Figure 2. The histograms show that the majority of incidents are due to tree roots (Valtetsiou) and ageing (Kosti Palama), with most incidents observed on mains (Valtetsiou) and house connections (Kosti Palama), respectively.

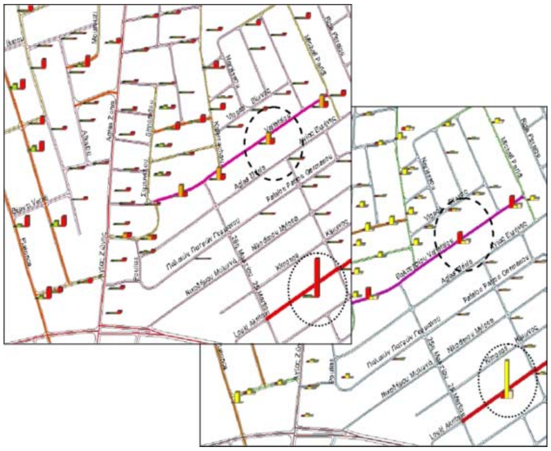

Figure 2 | Histograms of incident categorisation. Subscribers to the online version of *Water Science and Technology:Water Supply* can access the colour version of this figure from http://www.iwaponline.com/ws.

The above visual analysis and representation is coupled with numerical analysis of the hazard rate and survival plots, "stratified" by different logical groups. For example, survival analysis of the pipe incidents grouped by the type of incident (such as pipe deterioration, interference by others, tree roots, corrosion, etc.) reveals interesting patterns in terms of the causes for pipe failure. Should one examine the hazard rate over time (measured in days of presumed pipe age), then one can see that the rate with which the hazard for failure increases for pipes experiencing deterioration is faster than the hazard rate for pipes under "interference by others" (Figure 3). Also evident in the same plot of survival analysis (Figure 3), the hazard rate for pipes in the vicinity of tree roots picks up pace (larger slope) over time indicating that pipes in the proximity of tree roots should be replaced at shorter time intervals or otherwise risk failure (alternatively, tree roots become an issue for pipe failure as time progresses).

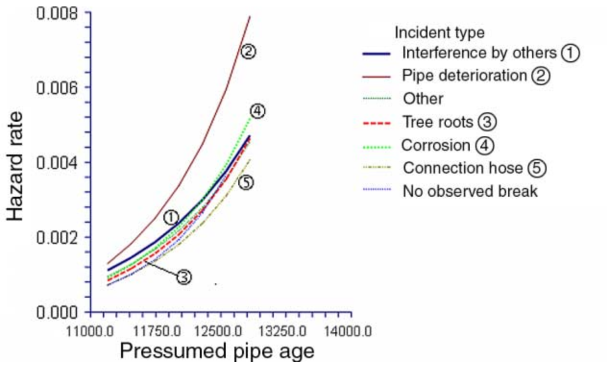

Figure 3 | Hazard rate plot, by incident type. Subscribers to the online version of *Water Science and Technology:Water Supply* can access the colour version of this figure from http://www.iwaponline.com/ws.

Asset management

This type of visually represented analysis furnishes the managing agency with an insight into the frequency, the severity, the categorisation and the reasons behind pipe breaks over time for all segments of the pipe network. In the case of the two street segments mentioned in this manuscript, the analysis can be summarised in linguistic terms of the form:

- Pipes located on Kosti Palama Street have a higher risk of failure than pipes located on Valtetsiou Street (therefore higher priority for maintenance/replacement).
- Pipes on Kosti Palama Street break primarily due to ageing (therefore need replacement). The majority of the pipe breaks are on house connections rather than water mains.
- Pipes on Valtetsiou Street break primarily due to tree roots in their vicinity (therefore the municipality needs to address the problem of trees close to pipes, either by cutting trees down, or by moving the pipes to a different location). The majority of the pipe breaks are on water mains rather than house connections.

The study further summarises collective knowledge acquired through data pattern recognition and neurofuzzy systems and lumps it into linguistic fuzzy rules (Deligianni 2006). Based on these rules:

- priority is given to areas in proximity of buildings of high pubic value (e.g. hospitals, schools);
- priority is then given to areas combining residential and industrial use;
- priority is then given to areas where other planned construction work is taking place (such as roadway rehabilitation) so as to maximise parallel work and minimise successive disruption;
- priority is then given to pipes with a high number of observed previous breaks (NOPB), based on our study;
- then, pipes with a diameter greater than 40 inches ($D > 40$) take precedence;
- these are followed by pipes made out of cast-iron, followed in priority by steel pipes;

- finally, replacement of pipes subjected to heavy traffic loads takes precedence.

CONCLUSIONS

The paper reports on the development of an integrated GIS-based decision support system for asset management of urban water distribution networks. The work, which is still under development, is now piloted for implementation in two cities in Cyprus. The water utilities involved aspire, through this implementation, to reduce water losses in their water distribution networks and to improve on the reliability of their systems. The underlying knowledgebase and integrated decision support tools (statistics, ANN, fuzzy logic, GIS) aim to support these utilities in their endeavours and benefit their consumers the most.

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