INTEGRATED GIS-BASED MANAGEMENT OF WATER DISTRIBUTION NETWORKS

Symeon Christodoulou[1], Pooyan Aslani [2], and Alexandra Deligianni[3]

ABSTRACT

The need to more intelligently and efficiently manage water distribution systems is increasingly more important to agencies managing such networks seeking a way to increase the reliability of their systems, the uninterrupted quality service of their "customers" and the cost-efficient operations and maintenance of the aging distribution networks. Repair and/or replacement of aging water mains, especially in urban environments, impose major expenditures on already financially strained municipalities and state governments, and the need to more actively engage in the monitoring and management of such networks is progressively increasing as existing distribution networks continue to age and therefore deteriorate.

The work included herein presents a framework for the management of urban water distribution networks based on both analytical and numerical modeling techniques and coupled with geographical distribution systems (GIS) for improved visualization and dissemination of relevant information to the management teams. The condition of elements within the water distribution network is assessed by means of mathematical modeling and artificial intelligence techniques, patterns in the underlying historical data are examined by means of artificial neural networks, knowledge is assembled and assessed by use of database management systems and fuzzy logic, and finally results are mapped on GIS for improved visualization and graphical querying of the implicit and explicit knowledge gained during maintenance and management of the water distribution network. The framework and processes developed and presented in this work were based on data collected in New York City and subsequently applied in Freeport (Long Island, NY), and the cities of Limassol and Larnaca (Cyprus).

This report is based upon work supported partly by the National Science Foundation (under Grant No. CMS-0118376) and partly by the Cyprus Research Foundation (under Grant No. AKGEN/1204/01).

KEY WORDS

Integrated management, water distribution networks, GIS, risk analysis, modeling.

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[1] Assistant Professor, Department of Civil & Environmental Engineering, University of Cyprus, Nicosia 1678, Cyprus, Phone (+357) 22892270, FAX (+357) 22892295, schristo@ucy.ac.cy

[2] Ph.D. candidate, Department of Civil Engineering, Center for Construction Management Technology, Polytechnic University, Brooklyn, New York 11201, USA, Phone 718/260-3864, FAX 718/260-3433, paslani@poly.edu

[3] Graduate student, Department of Civil Engineering, Systems Engineering and Management, Democritus University of Thrace, Xanthi 67100, Greece, adeligia@civil.duth.gr

INTRODUCTION

As the need to more intelligently and efficiently manage water distribution systems becomes increasingly more important to most urban utilities, who seek a way to increase the reliability of their systems and the cost-efficient operations and maintenance of the aging distribution networks, life-cycle costing and maintenance strategies become of paramount importance to these agencies. One of the most important dilemmas facing water distribution agencies is the question of repair or replacement of aging water mains, and the sequence of any such repairs as part of a long-term network rehabilitation strategy.

To-date a number of studies have been undertaken on infrastructure assessment and deterioration modeling, with the intent to assist owners of such systems improve their understanding of a system's behavior over time, its deterioration rate and it reliability with respect to identified presumed risk factors. The intent has always been to assist owners and operators of water distribution networks in arriving at "rehabilitate-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 corrosivity of the soil, the operating pressure and temperature, possible external loads (including highway traffic) and prior pipe breaks.

The work presented in this report outlines an integrated methodology and a decision support system for arriving at such "rehabilitate-or-replace" decisions, as part of a long-term capital improvement program undertaken by water utility agencies to improve on the reliability of the water distribution networks.

STATE OF KNOWLEDGE

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. Shamir and Howard (1979) reported an exponential relationship, Walski and Pellicia (1982) applied such exponential relationship to a data set stratified by material of pipe, and 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 review of numerous past studies by O'Day (1982) reinforced the belief that age is a strong predictor of pipe failure and further introduced location as a risk factor, while others (Kettler and Goulter, 1985) reported a strong inverse linear correlationship between failure rate and pipe diameter, and a moderate linear correlationship between breaks and pipe age. 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 (1988) to predict the probability of subsequent breaks given that at least one break had already occurred. Finally, Kleiner et al. (1998), and Kleiner and 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 analyze 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) with a small scale GIS-based implementation of the knowledge acquired reported upon by Fisenne (2004), as applied to the municipality of Freeport in Long Island, NY.

INTEGRATED SYSTEM FOR THE MANAGEMENT OF WATER DISTRIBUTION NETWORKS

SYSTEM FRAMEWORK

The developed integrated management system for the monitoring, rehabilitation and life-cycle costing of urban water distribution networks relies on the knowledge base of the New York City case study, the mathematical models developed for assessing risk of failure in water mains, and a neurofuzzy system that assembles and analyzes historical data acting as a decision support system (DSS).

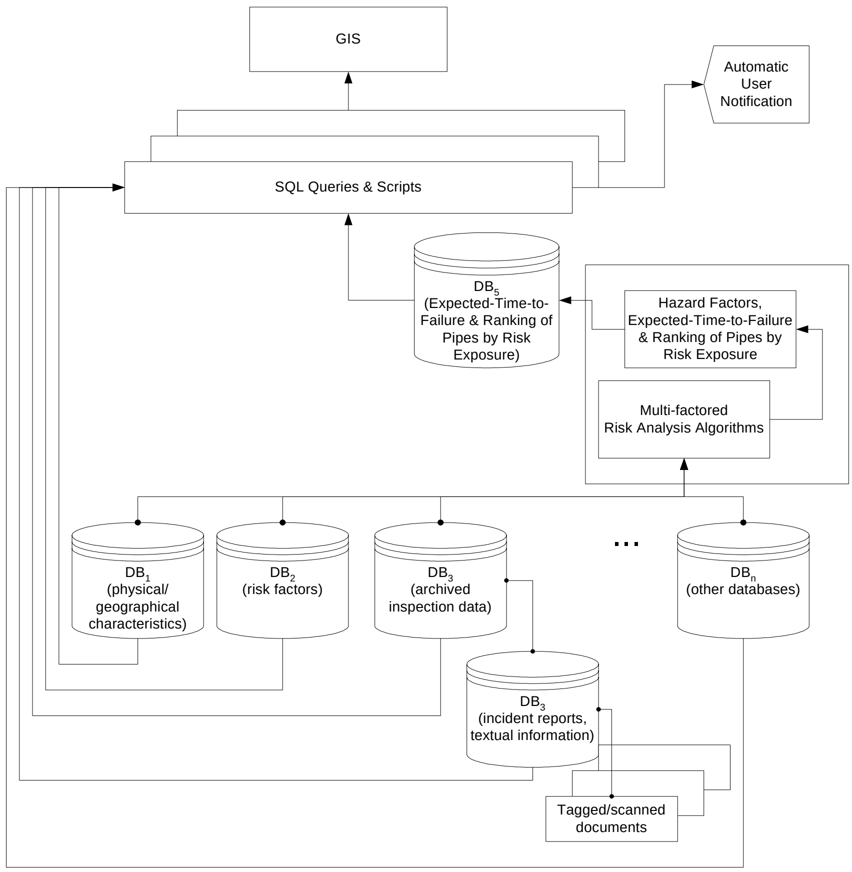

Figure 1: GIS-based management system for water distribution networks (database structure)

The underlying data on system characteristics (pipe diameter, length, material, date of birth, zoning, etc.), historical data (number of previous breaks), and other relevant characteristics of the system is shown in Figure 1. The database structure is the heart of the DSS, comprising the knowledge repository of the distribution network over time, as each data event is date/time-stamped to provide a chronology of events related to the risk of failure of each component. The databases are relational and integrated to minimize entry points by the users, standardize input, minimize risk of errors in data handling, and maximize automation of data analysis and reporting.

Central to this database structure are the geographical information system (GIS) and the mathematical models of risk assessment. The former aims the graphical representation of the risk in a visual GIS-based interface that enables users to quickly assess the probability of failure. Degrees of the risk of failure are color-coded and continually updated as time-related data is processed by the system (Figure 2). The data is processed by means of a combination of decision support tools, such as survival analysis, statistical analysis, artificial neural networks and fuzzy logic. A significant output of the described management system is a ranking of the system's components (pipes) in terms of risk of failure (Figure 2), so that users can assess the probability of failure and, in conjunction with associated costs, decide what the proper management strategy should be (replace or repair, and corresponding time horizon).

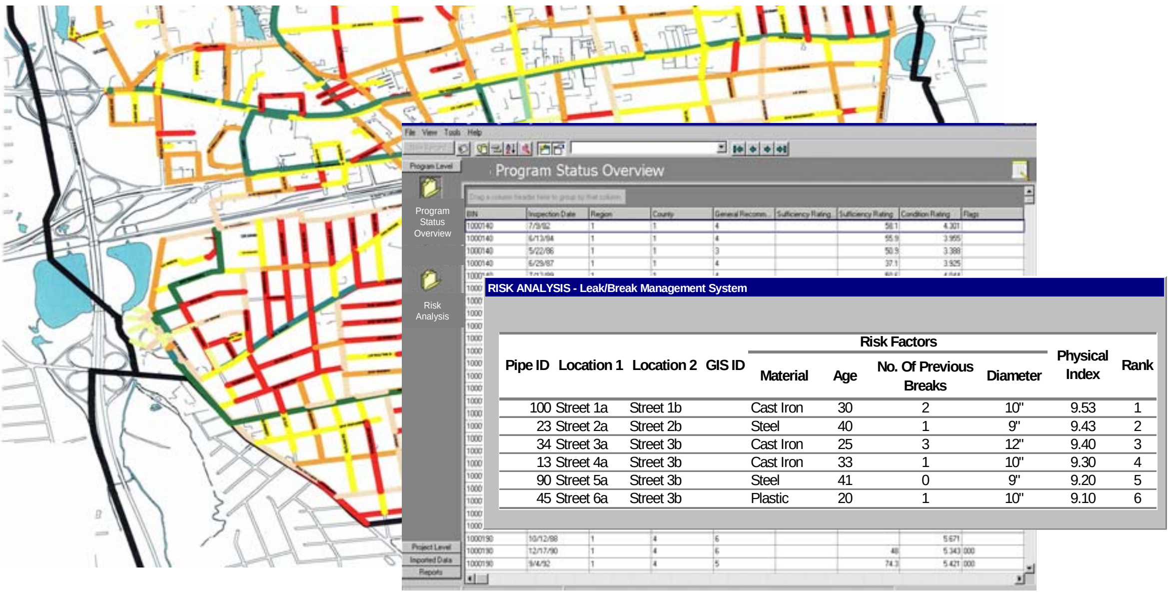

Figure 1: GIS-based management system for water distribution networks (graphical interface)

THE UNDERLYING NEUROFUZZY DECISION SUPPORT SYSTEM

The developed integrated management system for the monitoring, rehabilitation and life-cycle costing of urban water distribution networks relies on the knowledge base of the New York City case study, the mathematical models developed for assessing the risk of failure in water mains, and a neurofuzzy system that upon the assembly and analysis of the historical data it then acts as a holistic decision support system (DSS).

The present study is an extension of the study reported by Vanrenterghem (2003) and Christodoulou et. al. (2004) in which historical data spanning a 20-year period (1982 – 2002) and about 500 pipe breaks in a population of about 6,600 statistical individuals (breaks or not) was analyzed. The data included several presumed risk factors that, through statistical and numerical (ANN) analysis were reduced to eight significant factors: number of observed previous breaks, material, length, diameter, traffic load, proximity to highway, proximity to subway, and proximity to roadway/block intersection.

The ANN analysis identified the type of interrelationships between these risk factors, and the possible contribution to the "Break or Not" output, also projecting rough estimates of the "life cycle (in days)" output. A four-layer backpropagation model (2 hidden layers) was employed for the analysis (Figure 3).

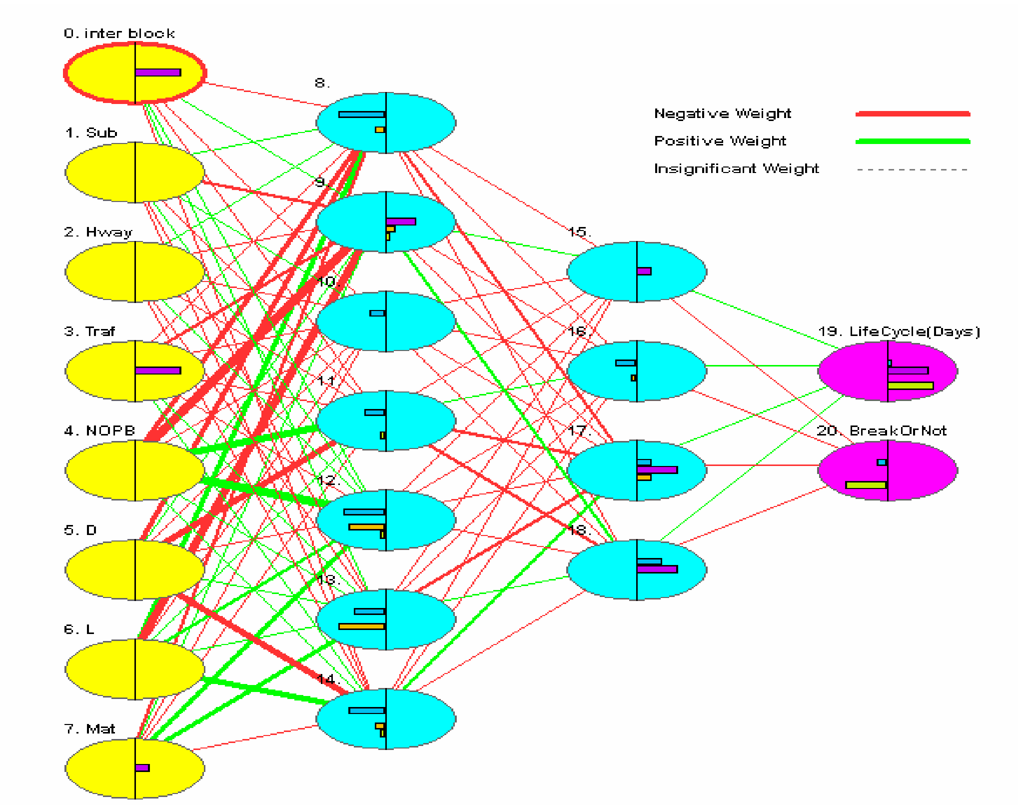

Figure 3: Artificial neural network (ANN) model of the risk factors for failure

The results of the ANN were then ranked according to their relative importance and contribution to the "Break or Not" output neuron (Figure 4). As Figure 4 depicts, the most important factors contributing to risk for failure are the number of previously observed breaks (*NOPB*), the material type (*mat*), the length (*L*) and diameter (*D*) of each pipe.

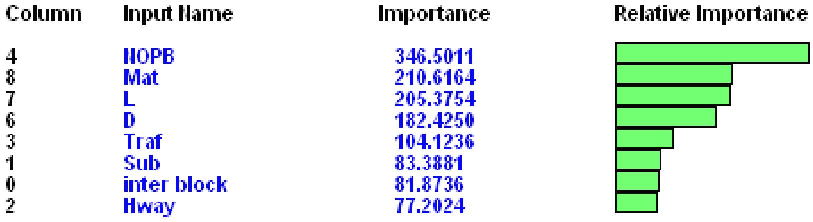

Figure 4: Ranking of risk factors based on artificial neural network (ANN) analysis

Since one of the primary goals was the creation of an integrated decision support system that can process historical data in a manner that will facilitate quick and intelligent strategic decisions on the maintenance of the water distribution network, the artificial neural network is complimented with a fuzzy system that fuzzifies the risk factors and transforms them into "expert rules" that can serve as the basis of the decision-making mechanism. The membership functions used for the fuzzification and defuzzification of the knowledge base are shown in Table 1 (Deliyanni 2006).

Table 1: Fuzzy inputs/output and associated membership functions

Fuzzy Neuron	**Membership Functions**	**Fuzzy Inputs and Data Ranges**			
Diameter	Triangular	"Small" (4-30)	"Medium" (20-48)	"Large" (40-72)	
NOPB	Triangular	"Small" (0-2)	"Medium" (1-4)	"Large" (3-9)	
Subway	Trapezoid	"0"	"1"		
Length	Triangular	"Small" (0.25-5.5))	"Medium" (4.5-14)	"Large" (10 -21)	
Material	Trapezoid	"1"	"2"	"3"	"4"
Traffic	Trapezoid	"0"	"1"	"2"	
Break Or Not	Trapezoid	"0"	"1"		

The aforementioned fuzzification and defuzzification process produces the "expert rules" tabulated in Table 2 (Deliyanni 2006), which aim to guide the water utility companies that administer the water distribution networks assess the risk of failure and develop replacement strategies for associated assets.

Table 2: Fuzzified "expert rules" for assessing the risk of failure of water distribution pipes

Fuzzy Rules
If D=small and NOPB=small and Sub=0 and Length= small and Mat=2 and Traf=1, then BreakorNot=0
If D=small and NOPB=small and Sub=0 and Length= small and Mat=1 and Traf=1, then BreakorNot=1
If D=large and NOPB=large and Sub=0 and Length= small and Mat=4 and Traf=2, then BreakorNot=1
If D=medium and NOPB=small and Sub=0 and Length= small and Mat=4 and Traf=2, then BreakorNot=0
If D=small and NOPB=small and Sub=0 and Length= medium and Traf=1, then BreakorNot=0
If D=small and NOPB=small and Sub=0 and Length= large and Mat=2, then BreakorNot=1
If D=small and NOPB=small and Sub=0 and Length= large and Mat=1 and Traf=0, then BreakorNot=0
If D=medium and NOPB=medium and Sub=0 and Length= small and Mat=4 and Traf=2, then BreakorNot=1
If D=large and NOPB=large and Traf=2, then BreakorNot=1
If NOPB=small and Mat=1, then BreakorNot=0
If D=small and NOPB=small and Sub=1 and Length= small and Mat=1 and Traf=2, then BreakorNot=0

CONCLUSIONS

The research described herein aims the development of an integrated GIS-based decision support system for assessing risk of failure and managing water distribution networks in urban environments. The work, which is still under development, is now piloted for implementation in two cities in Cyprus. The municipalities involved aspire, through this implementation, to reduce water losses in their water distribution networks and improve on the reliability of their systems. The underlying knowledgebase and integrated decision support tools (statistics, ANN, fuzzy logic, GIS) aim to support these utility companies in their endeavors and benefit their "clients" the most.

ACKNOWLEDGMENTS

This report is based partially upon work supported by the National Science Foundation (under Grant No. CMS-0118376) and upon work supported by the Cyprus Research Foundation (under Grant No. AKGEN/1204/01). Gratitude is also extended to the Democritus University of Thrace for their participation as part of the EU-funded System Engineering and Management Program.

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