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Fuzzy sets analysis for leak detection in infrastructure systems: a proposed methodology

Rustom Mamlook, Odeh Al-Jayyousi

Abstract This paper aims to propose a methodology for detecting problems in environmental and infrastructure systems using a fuzzy set technique. The proposed methodology was applied to a case study in water distribution systems for validation. Relative weights for three scenarios of leak detection were used, i.e. leakage, possible leakage, and no leakage. The study reveals that the major factors that affect leakage are: pipe age, pipe material, operational aspects, and demand patterns.

Introduction

Rehabilitation of infrastructure systems is characterized by being both probabilistic and costly. Determination of when and where to rehabilitate and how much to invest are vital questions for policy makers. Decision support systems (DSS) may be utilized to address these issues. After Zadeh's work on fuzzy sets (Zadeh 1965), many theories in fuzzy logic were developed. Since the 1970s Japan has been advancing the practical implementation of the fuzzy logic theory. The U.S. Space Administration has adopted fuzzy logic in space control decision making. Energy consumption could be analyzed using fuzzy sets (Oder et al. 1993). Moreover, engineering systems for energy and water consumption could be controlled using fuzzy rules (Mamlook et al. 1999, 2003; Akash et al. 1999; Al-Jayyousi and Mamlook 2003).

The significance of leak detection in environmental planning and management stems from the fact that many water scarce and arid countries such as Jordan have limited options for water resources development. Therefore, focusing on water supply and demand management options is deemed necessary as they offer more cost-effective and environmentally sound solutions. Much research have been conducted to assess various parameters of leak detection. Cole (1980) proposed the best indicator for leakage by using the minimum night ratio (MNR), which is defined as the ratio of the lowest water use rate at night to the average daily use. Siedler (1983) suggested that it was possible to distinguish between meter under-registration and leakage as a source of unaccounted-for water (UFW) by dividing metered domestic water use by metered population. Walski (1984) proposed a methodology for assessing the benefits of leak detection control. Germanpoulos and Jowitt (1989) and Jowett and Xu (1990) developed optimization models for the analysis of leak detection.

Vairavamoorthy and Lumbers (1998) developed an optimization model to minimize leakage in water distribution systems through the most effective settings of flow reduction valves. The subject of leak detection using state estimation procedures is also treated by Carpentier and Cohen (1993). Tucciarelli et al. (1999) estimated the water loss as small leaks and openings in different areas of a pipe network by using a simulation/optimization model. This paper intends to propose a methodology for assessing leak detection in a water distribution network based on a fuzzy set technique. Two case studies are presented to illustrate the proposed methodology.

Problem statement

The infrastructure systems, such as water, sewers and highways, of many countries in the world are deteriorating. This in turn will negatively affect the built environment and pose a threat for future generations. Predicting possible problems in infrastructure systems, such as water distribution systems, represents a significant effort in pollution control and prevention.

The root causes for the water crisis in Jordan may be defined as water scarcity, variability and aridity. Environmental problems in Jordan are mainly related to pollution of irrigation water caused by inadequately treated wastewater, industrial effluents, and to soil salinity.

In reality, it is difficult and rather simplistic to look at water issues in a fragmented manner, since integrated management of water resources must address multiple effects and externalities to ensure and sustainable development. Moreover, such an endeavor is subject to constraints due to existing legal and institutional structures, which are often not conducive to change.

In Jordan there is a water deficit, which amounted to about 200 MCM per year (Al-Jayyousi 2001; Al-Jayyousi and Shatanawi 1995; Al-Jayyousi and Mohsen 1999). The extent of the water deficit led the government to adopt an

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R. Mamlook (✉)
Department of Computer Science, Zarka Private University,
P.O. Box 2000, 13110 Zarka, Jordan
E-mail: RSTMAMLK@HOTMAIL.COM

O. Al-Jayyousi
Civil Engineering Dept., College of Engineering, Applied Science
University, Amman, Jordan

emergency plan and to re-allocate water from irrigation to domestic uses. Others crisis management measures include:

1. Rationing of water in summer, which implied interruption of water for many users
2. Desalination of brackish water and the development of fossil water
3. Water supply and demand measures which included water pricing, public awareness, and the rehabilitation of water networks to address the high percentage which amounted to about 50% of unaccounted-for water (UFW)

This research intends to address the UFW problem by proposing a methodology to assess and predict the water leakage in water distribution systems using fuzzy sets.

Proposed methodology

Synthetic evaluation is an important application of the fuzzy transform used in developing the extension principle. The term synthetic is used here to connote the process of evaluation whereby several individual elements and components of an evaluation are synthesized into an aggregate form: the whole is a synthesis of the parts. The key here is that the various elements can be non-numerical, and the process of fuzzy synthesis is naturally accommodated using synthesis evaluation. An evaluation of an object, especially an ill-defined one, is often ambiguous and vague. Since a numerical evaluation is often too unacceptable, too complex, and too ephemeral (transient), the evaluation is usually described in natural language terms. To formalize the fuzzy synthesis evaluation, let *F* be a universe of factors and *P* be a universe of evaluations, so

$$F = \{F_1, F_2, ..., F_N\} \text{ and } P = \{P_1, P_2, ..., P_M\}$$

Let $R = \{r_{ij}\}$ be a fuzzy relation as in Table 1, where $i = 1, 2, ..., N$ and $j = 1, 2, ..., M$. Suppose we introduce a specific water distribution system into the evaluation process on which the expert engineer has given a set of "weights" (w_i) for each of five factors as listed below:

- Pipe type (PT)
- Pipe age (PA)
- Pumping system (PS)
- Pipe diameter (PD)
- Demand (D)

Table 1. Sample matrix for fuzzy pairwise relation

	P_1	P_2	...	P_M
F_1	r_{11}	r_{12}		r_{1M}
F_2	r_{21}	r_{22}		r_{2M}
.	.	.	.	.
F_N	r_{N1}	r_{N2}		r_{NM}

Table 2. Matrix for fuzzy water distribution system pairwise relation

	L	NL	PL
PT	0.5	0.2	0.3
PA	0.5	0.3	0.2
PS	0.4	0.1	0.5
PD	0.1	0.4	0.5
D	0.2	0.3	0.5

The quantification of the above parameters is shown in Table 2. We ensure for convention that the sum of weights is unity. Each of these weights is actually a membership value for each of the factors, F_i in {pipe type (PT), pipe age (PA), pumping system (PS), pipe diameter (PD), and demand (D)}, and they can be arranged in a fuzzy vector, *W*. So we have

$$W = \{w_1, w_2, ..., w_N\} \text{ where } \sum\nolimits_{i=1}^{N} w_i = 1 \qquad (1)$$

The process of determining a value for a specific water system distribution is equivalent to the process of determining a membership value for the water system in each of the evaluation categories, P_j in

- Leakage (L)
- No leakage (NL)
- Possible leakage (PL)

This process is implemented through the composition option

$$E = WOR \qquad (2)$$

where *R* is a fuzzy relation as in Table 1, *W* is a set of weights as in Eq. (1), *O* is the max–min composition operation, and *E* is a fuzzy vector containing the membership values for the water system in each of the P_j in {leakage, no leakage, and possible leakage} evaluation categories. If the evaluation expert engineering team applies a factor of 0.4 for PT, 0.3 for PA, 0.6 for PS, 0.7 for PD, and 0.5 for D, which together form the factor, *W*, then the composition

$$E = WOR = \mathrm{MAX}\{e1, e2, e3\} = \mathrm{MAX}\{0.1, 0.2, 0.3\}$$

where *e*1, *e*2, and *e*3 are the membership values in the categories leakage (L), no leakage (NL), and possible leakage (PL) respectively. In addition,

$$e1 = \mathrm{MAX}\left\{\begin{array}{l}\mathrm{MIN}(0.4, 0.4), \mathrm{MIN}(0.3, 0.5), \mathrm{MIN}(0.6, 0.4), \\ \mathrm{MIN}(0.7, 0.1), \mathrm{MIN}(0.5, 0.2)\end{array}\right\},$$

$$e2 = \mathrm{MAX}\left\{\begin{array}{l}\mathrm{MIN}(0.4, 0.3), \mathrm{MIN}(0.3, 0.2), \mathrm{MIN}(0.6, 0.2), \\ \mathrm{MIN}(0.7, 0.5), \mathrm{MIN}(0.5, 0.5)\end{array}\right\},$$

$$e3 = \mathrm{MAX}\left\{\begin{array}{l}\mathrm{MIN}(0.4, 0.3), \mathrm{MIN}(0.3, 0.3), \mathrm{MIN}(0.6, 0.4), \\ \mathrm{MIN}(0.7, 0.4), \mathrm{MIN}(0.5, 0.3)\end{array}\right\},$$

results in an evaluation vector that has its highest membership in the category "possible leakage".

The fuzzy logic detection was performed to assess three rules, i.e. "leak", "no leak", or "possible leak", in water distribution systems in Jordan. We considered the factors that affect the detection of leak (Fig. 1). Figure 1 is based on actual data obtained from field measurements for hydraulic analysis in Amman City (SBA 1996). Our objective is to make the decision of detecting leak, no leak,

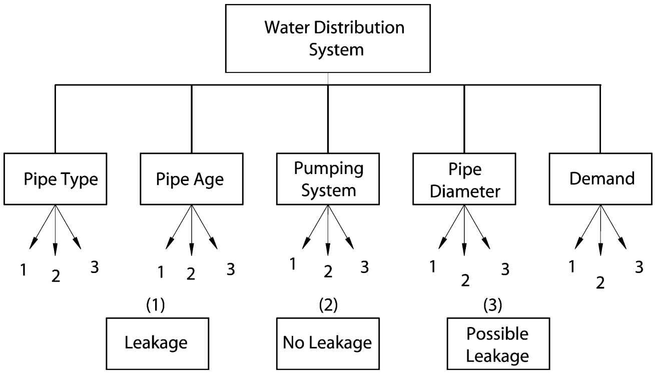

Fig. 1. Leakage detection fuzzy system structure

or possible leak of the water distribution systems in Jordan.

The fuzzy logic decision maker method described above was used to compare water distribution system detection options (p_1 = leak; p_2 = no leak; p_3 = possible leak) in Jordan to detect leak in the water distribution system. Many factors affect this decision. They include F_1 = pipe type, F_2 = pipe age, F_3 = pumping system, F_4 = pipe diameter, and F_5 = water demand (Fig. 1).

Case studies: leak detection in Jordan

Background

Leakage from distribution systems represents a significant loss in water resources. Specifically, unaccounted-for water (UFW) is estimated to be about 53% in Jordan (WAJ 1997, 1998, 1999). As a result, a comprehensive water infrastructure rehabilitation is under way in Jordan to minimize UFW. The water loss can occur either by the total failure of one or more pipes or by small openings and leaks located in the pipe walls and around the pipe junctions.

Of the many factors that affect leakage, it is only pipe pressure that can be controlled when pipes have been laid. Hence, it is recommended that where pressure reduction is feasible and cost effective it should be applied on its own or in conjunction with other methods of leakage control (e.g., passive control, routine or regular sounding, district metering, waste metering, and combined district and waste metering) (Vairavamoorthy and Lumbers 1998).

The growth in water demand in Jordan has led to the exhaustion of surface water and to the over extraction of groundwater. By overdrawing its groundwater aquifers, Jordan is losing an irrecoverable supply, increasing water costs and causing deterioration in the water quality. Efforts to overcome the unsatisfied water demand in Jordan include supply enhancement, optimization of water use in all sectors, and demand management. Apart from the conventional ways to address this issue through supply augmentation, many measures have been taken to enhance water supply and reduce demand. These include: wastewater reuse, desalination, water harvesting, cloud seeding, and public awareness.

An extensive leakage detection and identification study in a small test system for a complete 24-h period of operation has been carried out in Jordan. The measurements of pressures and flows are supplied to the system operator via real-time telemetry systems. A limited number of measurements together with predictions of consumptions (referred to as pseudo-measurements) were used to calculate the overall state of the water distribution network. This is accomplished by using state estimators that provide a means of combining diverse measurements by relating them to the mathematical model of the system (Bargiela 1984; Sterling and Bargiela 1984a,1984b; Gabrys and Bargiela 1995). The procedure for the quantification of the inaccuracy of the state estimates caused by the input data uncertainty was termed the confidence limit analysis (CLA) (Bargiela and Hainsworth 1989).

In this paper a fuzzy recognition system, utilizing information from the state estimation and CLA procedures, is proposed as a means of faults detection and identification in water distribution networks.

Two broad categories of faults occurring in water distribution systems have been considered in the course of our investigations. The faults due to malfunctioning of transducers and telecommunication equipment are referred to as the measurement errors; the faults due to leakages and wrong status of valves (invalidating the system model) are referred to as the topological errors.

One of the early attempts to analyze bad data in water systems state estimation has been made by Bargiela (1984). In this work it has been argued that to distinguish between the measurement and topological errors, a magnitude and sign of the weighted measurement residuals at each end of a pipe should be analyzed.

The leakage detection in this work is based on a comparison of the consumption values estimated on-line, using real flow measurements, with the pseudo-measurements that represent standard consumptions in these nodes in a normal operating state (without any leakage present). These pseudo-measurements had been obtained from a simulation of a 24-h period of the normal network operations. The weights in the weighted least-squares criterion were chosen in such a way that the errors occurred in nodal mass balance equations and represented an increase in nodal consumptions. Occurrence of a set of significant errors in some areas of the network was treated as a sign of the presence of a leakage in this area. No attempts were made to further process these errors to find a reduced number of the most likely pipe(s).

From the above discussion it is evident that the detection and identification of topological errors still presents a significant challenge. Analysis of precise numerical results of state estimation is useful but tends to ignore the picture of the overall system state which is something that experienced human operators primarily focus their attention on before analysis.

In an effort to combine the ability of fuzzy systems to cope with uncertain and ambiguous data with the computational efficiency, learning, and pattern recognition ability of neural networks (NNs), a general fuzzy min–max NN for clustering and classification has been developed by Gabrys (1997). This paper utilized this concept for data aggregation to conduct the comparisons and weighting of variables.

The five parameters that were analyzed in the leak detection case study include: pipe type, pipe age, pumping system, pipe diameter, and water demand. Three basic rules for leakage were studied. These rules are:(Table 2)

- Rule 1: leakage (L)
- Rule 2: no leakage (NL)
- Rule 3: possible leakage (PL)

Case study 1

Criteria of choice of pilot zones

The selected pilot areas reflect the following criteria:

1. Housing and socio-economic characteristics, which are representative of other areas in the study area.
2. Network characteristics such as pipe material, diameter and age which are representative of other areas.
3. Topography and operating pressures, which are representative of other areas.
4. The three selected pilot areas were located in Irbid City and the towns of Edoun and Al-Masharea'.

Pilot area no. 1 (Edoun)

Edoun town is very representative of the main towns of the study area in terms of:

- The population is about 14,560 inhabitants (1994 census). Edoun pilot area represents towns with a population ranging between 10,000 and 20,000 inhabitants. This range of 15 towns covers 21% of the total population of the study area.
- Typology of the distribution network which is at 80% exposed as 54% of the networks of the whole study area.
- Material of pipes, which are ductile 200 mm, steel pipes (100–400 mm) and galvanized iron pipes (50–100 mm), for the whole of the towns within the study area.
- Age of pipes (about 25 years).
- It is a fairly newly developed community with medium socio-economic standards of living. Types of houses are of small and medium size houses and apartments with reef water-tanks, but very few underground storage tanks. There are no trade centers and factories within the town vicinity.
- One of the advantages of the topographical characteristics of Edoun is that the town has inter-connected boundaries with nearby towns and with towns on its eastern and western boundaries.
- The pilot area was selected to include almost all of the town of Edoun. Small parts at the northwestern and southeastern boundaries of the town were excluded so as to provide a reasonably isolated area.

The evaluation expert engineering team applies a factor of 0.6 for PT, 0.1 for PA, 0.3 for PS, 0.6 for PD, and 0.4 for D, which together form the factor, W, then the composition, Eq. 2: $E=WOR=\mathrm{MAX}\{0.5, 0.4, 0.6\}$ results in an evaluation vector that has its highest membership in the category "possible leakage".

Case study 2: Al Masharea'

Al-Masharea' village is very representative of the main villages of the study area in terms of:

- It represents towns of less than 10,000 inhabitants which covers 50% of the total population of the study area.
- Al-Mashara' pilot area is located in an environment of special characteristics. It is one of the large towns with rural characteristics. It is located in North Ghor area, which is a region in Jordan with very special topographic characteristics.

Its elevation is 150 m below sea level. It has a population of 130,096 inhabitants as per the 1994 census.

- Living standards of Al-Masharea': population can be categorized as medium-low to low according to the population assessment of the study area. Consumers occupy a wide range of buildings such as domestic, shopping centers, schools, public and administrative buildings and mosques.
- Material of pipes, which are PVC (50–100 mm) and asbestos (150–200 mm) for all the villages within the study area.
- Topology of the distribution network of Al-Masharea'. As is the case in towns and villages of North Ghor, it is totally buried, which is somewhat different from that in most towns and villages of the study area.
- Topography and operating pressures, which are representative of other areas.

The evaluation expert engineering team applies a factor of 0.2 for PT, 0.4 for PA, 0.3 for PS, 0.5 for PD, and 0.4 for D, which together form the factor, W, then the composition, Eq. (2): $E=WOR=\mathrm{MAX}\{0.4, 0.3, 0.5\}$ results in an evaluation vector that has its highest membership in the category "possible leakage".

Environmental policy implications

The policy issues (questions) raised in this research may be summarized as follows:

1. When should we rehabilitate water distribution systems (WDS)?
2. When should we construct a new WDS and how much money should be allocated?
3. What is the acceptable unaccounted-for water (UFW) for a WDS?
4. How to ensure sustainable water management in a WDS?
5. How to enhance the reliability of a WDS by optimizing various system parameters (pipe material, pipe type, pumping pattern, treatment)?

The findings of this research have many environmental policy implications. These include:

1. The methodology for leak detection adopted in this paper helps to ensure a sustainable development infra-

Table 3. Ultrasonic district meter reading—Edoun area

Period h:m:s Recorded data	Number of readings	Date d/m/y	Time of Stopping h:m
00:05:00	179	31/01/1997	10:50
00:05:00	100	31/01/1997	19:20
00:05:00	33	01/02/1997	17:20
00:05:00	30	01/02/1997	20:00
00:05:00	28	01/02/1997	22:10
00:05:00	3	01/02/1997	22:30
00:05:00	129	02/02/1997	09:20
00:05:00	13	02/02/1997	10:30
00:05:00	22	02/02/1997	12:20
00:05:00	31	02/02/1997	15:10
00:05:00	30	02/02/1997	17:40
00:05:00	761	05/02/1997	10:38
Total number of readings	1,359		
Campaign starting date		31 January 1997 at 20:00 h	
Campaign ending date		5 February 1997 at 10:38 h	
Readings recorded		Every 5 min	
Duration of campaign		4 days 14 h 38 min (5.6 days)≈134 h	
Total number of readings recorded		1359	
Discharge			
Minimum		50.94 m^3/h	
Maximum		324.59 m^3/h	
Average		107.13 m^3/h	
UFW: 58%			

Table 4. Ultrasonic district meter reading—Al-Masharea'

Period h:m:s Recorded data	Number of readings	Date d/m/y	Time of Stopping h:m
00:05:00	64	20/03/1997	14:30
00:05:00	504	22/03/1997	11:10
00:05:00	125	23/03/1997	08:25
00:05:00	203	24/03/1997	10:15
00:05:00	6	24/03/1997	12:20
00:05:00	10	24/03/1997	13:15
00:05:00	201	25/03/1997	09:55
00:05:00	471	27/03/1997	08:25
Total number of readings	1,584		
Campaign starting date		20 March 1997 at 14:35 h	
Campaign ending date		27 March 1997 at 10:20 h	
Readings recorded		Every 5 min	
Duration of campaign		6 days 23 h 10 min (6.97 days)≈168 h	
Total number of readings recorded		1,584	
Discharge			
Minimum		0.00 m^3/h	
Maximum		92.34 m^3/h	
Average		38.43 m^3/h	
UFW: 45%			

structure systems by reducing the probability of pollution due to leakage.

2. Having the range of possible leakage assessments, i.e. leakage, no leakage, possible leakage,) enables policy makers to select sound policies with various trade-offs.
3. The proposed approach helps managers to allocate the right financial resources to invest in infrastructure projects. This is crucial when considering the opportunity cost and the limited resources for capital improvements in the developing countries.
4. The assessment of the condition of WDS helps determine the level of service and the reliability of the infrastructure system. This implies that low values of UFW imply high system performance and less negative environmental impacts.
5. The model helps policy makers plan preventive maintenance for infrastructure systems such as a

WDS. This in turn contributes to sustainable water management.

Conclusions and discussion

One of the advantages of the fuzzy logic decision maker (FLDM) method presented here is that it uses fuzzy sets that enabled us to a condense large amount of data into smaller set of variable rules. Also the FLDM method used minimum and maximum operations, which are easier and faster than those are used by other methods.

The prediction, prevention and control of leakage in infrastructure systems such as a water distribution network are of vital importance. This research has proposed a methodology for the prediction of leakage of water using a fuzzy set technique. The two case studies presented reveal the following:

1. Using the proposed methodology enabled us to predict UFW in water systems in a reasonable manner.
2. Decisions reached reflect the adequacy of this method.

The fuzzy sets enabled us to condense a large amount of data, collected to detect leaks or possible leaks in the water distribution systems in Jordan, into a smaller set of variable rules.

The various characteristics for each case study were synthesized and converted into relative weights using the fuzzy set method. Tables 3 and 4 illustrate the basic readings and calculations for leakage and UFW. Based on these tables UFW was estimated to be 58% and 45% for cases 1 and 2 respectively. Based on our proposed methodology it was revealed that there is a close correlation between the actual and predicted values of UFW. The actual and predicted values for case 1 were 58% and 60% respectively. Also for case 2 the actual and predicted values were 45% and 50% respectively.

The fuzzy set analysis for both cases reveal possible leakage as confirmed by the experimental data in Tables 3 and 4. The application of the fuzzy set methodology offers reasonable prediction and assessment for leakage in water systems.

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