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Evaluating leakage potential in water distribution systems: a fuzzy-based methodology

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ABSTRACT

Loss of water due to leakage is a common phenomenon observed in all water distribution systems. However, the water loss can be reduced to an acceptable limit by improved understanding of leakage mechanisms and pathways, and the influencing factors that lead to leakage. This study proposes a methodology to estimate leakage potential (LP) in a water distribution system (WDS). The study has identified various factors which are directly and/or indirectly associated with LP in a WDS. The research has defined a selected set of influencing factors as fuzzy variables and has developed a fuzzy rule-based (FRB) model using Mamdani inferencing algorithm. The impact of influencing factors varies under different operating pressure, therefore a generalized methodology has been proposed. The proposed methodology has been implemented for a real WDS in Bangkok (Thailand). To evaluate the impacts of uncertainties of influencing factors on LP, Monte Carlo simulation-based sensitivity analysis has been carried out. It has been concluded that the operating system pressure and age of the network are the two most important factors that contribute to LP of a WDS. The proposed model will help water utility managers to prioritize their network rehabilitation strategies and to establishing an efficient active leakage control program.

Key words | fuzzy sets, leakage potential, Monte Carlo simulation, water distribution system, water mains

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INTRODUCTION

Water supply systems (WDSs) are the lifeline of urban and rural communities. A WDS supplies water from the sources to the consumers in a city/community like arteries supply blood in a human body. However, a significant percentage of water is being lost from many WDSs through leakage while travelling from water treatment plants to the consumers. The global water supply and sanitation assessment report (WHO-UNICEF-WSSCC 2000) estimated that the typical value of non-revenue water in Africa, Asia, Latin America and Caribbean and in North America are 39, 42, 42 and 15% respectively. One of the main components of these is lost water through leakages (Farley & Trow 2003).

There is no single reason for occurrence of leakage in a WDS. There could be numerous physical, environmental and hydraulic factors that pose threats or make WDSs vulnerable to cause leakage. Different external (to the network) factors, network physical components, workmanship quality and network operating practices directly or indirectly influence the leakage. External factors, such as traffic loading, influence the pipe failure due to vibration and heavy loading over the buried pipes. Soil types and its permeability influence the length of time a leak is allowed to continue as well as leakage flow rate. Groundwater tables and temperature influence the moisture contents which may have potential impacts on the breakage and leakage (Farley 2001). Physical components such as number of service connections, water meters, joints, material of the physical components, different type of demand and many

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others influence leakage significantly (Farley 2001; Lambert 2002; Tabesh *et al.* 2009). Factors such as the operating system pressure and the age of the network increase the leakage rate (Fares & Zayed 2009). Similarly, the poor workmanship of different network components such as meters, valves and pumps can be significant contributors to leakage in WDSs (Furness 2003).

To assess the effect of each factor on the leakage in a WDS, it is necessary to have a good monitoring system and a well established water leak detection and management system which are quite uncommon in most of the small-sized WDSs, or even in many bigger systems in the developing countries. However, the utility managers of those communities always want to have the tools and techniques to understand the impacts of different factors on leakage and leakage potential (LP) of their distribution systems.

Farley & Trow (2003) discussed different leakage pathways, mechanisms of leakage formulation, and relationship of pressure with leakage. Lambert (2001) showed the relationship of leakage with the operating system pressure. He developed the burst and background estimate (BABE) – a component based leakage volume estimation methodology. However, these authors have not studied the likelihood (potential) of occurrence of leakage. Fares & Zayed (2009) studied risk for failure of a whole distribution system using fuzzy-based approach. They presented a framework to evaluate the risk of water main failure using hierarchical fuzzy expert system. However, they did not include small leakage such as background leakage in their analysis. Rogers & Grigg (2006) developed a pipe failure assessment tool to prioritize pipe replacement in a water distribution system based on existing pipe inventory and break data from existing records of the utility organization. However, they did not study leakage potential for the distribution system. Mamlook & Al-Jayyousi (2003) proposed a technique to detect leakage in WDS using fuzzy synthetic evaluation.

Numerous other studies have also been reported in the literature that discussed the concepts related to WDS reliability. However, most of these studies focus on the failure of the WDS integrity. Very little research has been reported in evaluating LP of a WDS. Sadiq *et al.* (2010) proposed a framework for modeling the potential for water quality failures in distribution networks. However, no significant literature has been reported for evaluating LP for a WDS.

This research employed the concept of risk to assess the leakage potential. Risk is defined as a product of likelihood of an undesirable event and its related consequences (Sadiq *et al.* 2004a, b). However, in this study, consequences have not been modeled, rather only the likelihood or leakage 'potential' has been modeled. The term 'potential' for leakage has been used to refer to the 'possibility' or 'likelihood' of leakage. The scale of 'potential' is defined as a continuous interval of [0 1] or [0 100%]. A 100% LP of a WDS means that the production volume and LP are same in that WDS. If 100% LP becomes effective to a WDS, no water will be travelled to the tap of any customer. Using the concepts of risk and fuzzy set theory, this research aims at developing a new tool for water utility managers for evaluating LP in different parts of WDS under limited data and resources. The tool will help them to prioritize their active leakage control (ALC) and rehabilitation strategies.

METHODOLOGY

The proposed methodology requires identification of different leakage influencing factors and aggregation of those factors under varying operating system pressure. To aggregate the influences of each factor, a hierarchical relationship structure has been developed. A fuzzy rule-based (FRB) inferencing system has been used to aggregate the influences of each factor. To model the behavior of different influencing factors under varying operating system pressure, a pressure adjustment factor (PAF) has been developed and incorporated with the aggregation process.

Framework

Figure 1 shows four levels/generations hierarchical structure of leakage influencing factors and their interrelationship. The LP is in the first generation whereas the basic contributory factors are either in the third or fourth generation. Based on the literature survey and state-of-the-practice information, a list of 24 basic factors has been

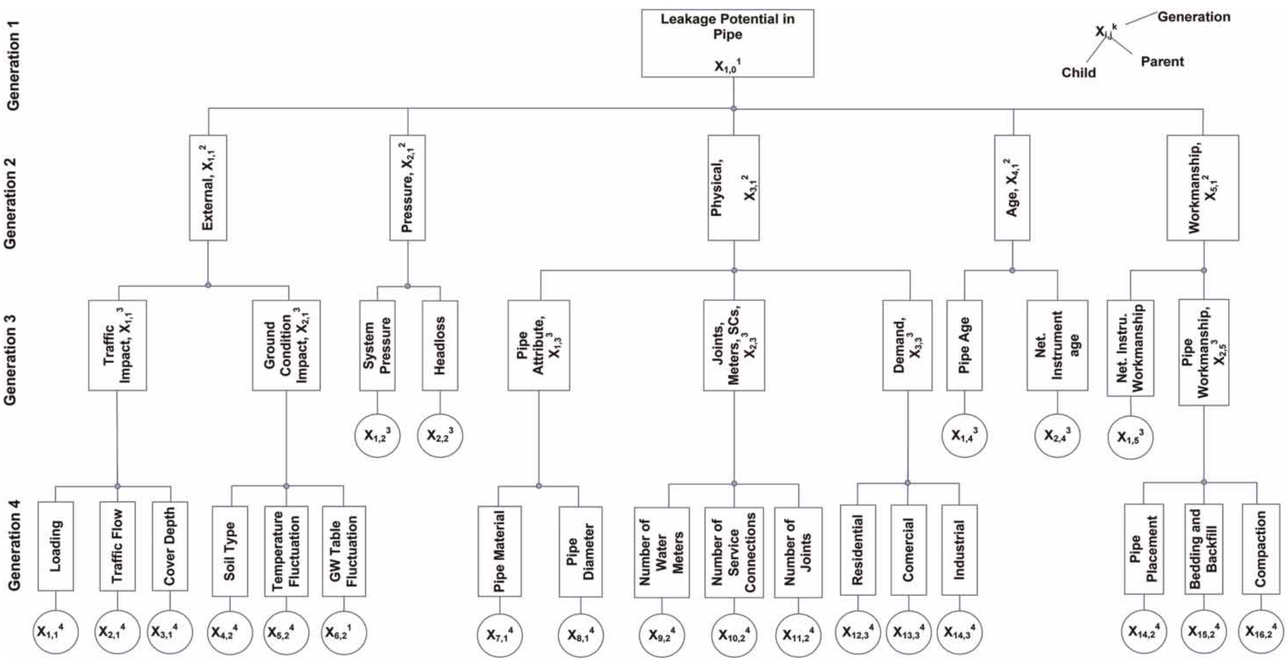


Figure 1 | Hierarchical structure of selected leakage influencing factors.

identified which directly (e.g. pressure) and/or indirectly (e.g. traffic movement) influence the leakage. The inter-relationships between basic and dummy factors have been expressed using Meta language developed by Sadiq *et al.* (2004a, b, 2007). Each element of the hierarchical structure has been expressed as $X_{i,j}^{k}$, where, X represents the leakage influencing factors, i represents the child, j for parent and k denotes the generation of the basic influencing factors. Both basic (for which data can be obtained) and dummy/intermediate factors in a hierarchical structure are composed of a 'parent' and 'children' relationships. Factor with no parents is the total 'LP for the system' and factors with no children are the basic leakage influencing factors.

Among 24 factors, the influence of 22 basic factors, except pressure exponent and reference pressure, propagated through these four generations (Figure 1). Leakage flow rate is proportional to a power (exponent) relationship of system pressure (Equation (4)). The power (exponent) of the pressure of that relationship is termed as pressure exponent. Pressure exponent and reference pressure influence LP taking part in the calculation of pressure adjustment factor provided below under Pressure adjustment.

The proposed methodology has two main parts. In the first part, FRB modeling has been carried out and in the second part, a PAF has been calculated to model the influence of varying pressure to the different factors. Calculated PAF has been incorporated within FRB modeling by multiplying with the output of basic influence factors. Each part of the methodology has multiple stages. Details of the stages have been presented in the following sections. All stages have been implemented by using MATLAB 7.9 Fuzzy Inferencing Toolbox together with the MATLAB traditional coding environment (MathWorks 2010).

Fuzzy rule-based modeling

Fuzzy sets are used to deal with vague and imprecise information (Zadeh 1965). Fuzzy set theory is widely applied to solve real-life problems that are subjective, vague, and imprecise in nature (Yang & Xu 2002; Smithson & Verkuilen 2006). Since its conceptualization, it has been used in various engineering applications including in civil engineering. It is successfully implemented for the structural damage analysis, vibration control of flexible structure, cement rotary kiln, concrete analysis and design, water quality modeling and leakage detection (Gad & Farooq 2001; Sadiq *et al.* 2007; Islam *et al.* 2011). Four steps are required to implement FRB modeling: fuzzification, inferencing, defuzzification and normalization.

Fuzzification

Fuzzification is a step that transforms all commensurate or non-commensurate data into a homogeneous scale by assigning memberships with respect to predefined linguistic variables (Khan & Sadiq 2005; Chowdhury *et al.* 2007). To fuzzify data, generally triangular fuzzy numbers (TFN) or trapezoidal fuzzy numbers (ZFN) are used (Lee 1996; Islam *et al.* 2011). For this study, all the leakage influencing factors have been modeled using TFN and ZFN.

Definitions of different leakage influencing factors in different granularity levels have been presented in the form of thresholds shown in Figures T1 and T2 in Table 1. For each leakage influencing input, type of fuzzy number and threshold values are based on a literature review and contacting experts from the water industry.

Most of the membership functions have three levels of granularity which are expressed through linguistic variables: *low*, *medium* and *high*. However, for some relatively more sensitive input factors and their output (e.g. pressure, age, LP), five-level granularity for membership functions (*very low*, *low*, *medium*, *high* and *very high*) are defined.

Fuzzy inferencing system

Two fuzzy rule-based inferencing algorithms are very common: the Mamdani and the Takagi, Sugeno and Kang (TSK) methods (Mamdani 1977; Ross 2004). The Mamdani algorithm is the most common in practice and it has also been implemented in this study. In the Mamdani algorithm, the relationships between fuzzy variables can be represented by if-then rules in the form 'If antecedent proposition then consequent proposition'. The theoretical background of fuzzy rule-based system is available in various literature (e.g. Ross 2004; Sadiq *et al.* 2004a).

Defuzzification

Defuzzification is a procedure for determining the most representative crisp value of the fuzzy set output taken as an isolated entity (Saade & Diab 2002). Among several defuzzification techniques, the center of gravity (COG) is the most popular due to its simplicity and easiness for programming, less use of computer resource and reasonable output (Fares & Zayed 2009). Therefore, this study also applies COG method. The value of the crisp LP value has been calculated using the following equation:

$$Crisp\,Lp = \frac{\sum_1^k A^k D^k}{\sum_1^k A^k} \tag{1}$$

where, A is the truncated area taken from membership function based on inferencing rules, D^k is the moment arm of the truncated area and k is the membership function.

Normalization

For absolute favorable condition, the calculated LP should be close to zero and for absolute unfavorable condition the calculated LP should be close to the unit value. However, using the COG method does not produce these two extreme values due to its nature of approximation. Therefore, produced results using this method could be confusing to the people who are not familiar with the method. To avoid this confusion and to make easier interpretation of the results, the calculated crisp value has been normalized between 0 and 1 by using Equation (2):

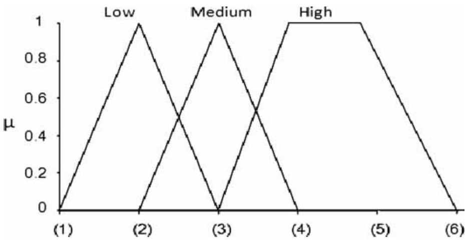
$$R_N = \frac{R^{cog} R^{cog}_{min}}{R^{cog}_{max} - R^{cog}_{min}} \tag{2}$$

where R_N is the normalized LP for any condition; R^{cog} is the LP for any condition calculated by COG method; R^{cog}_{min} is the minimum LP for extreme favorable condition calculated by COG method; and R^{cog}_{max} is the maximum LP for extreme unfavorable condition calculated by COG method.

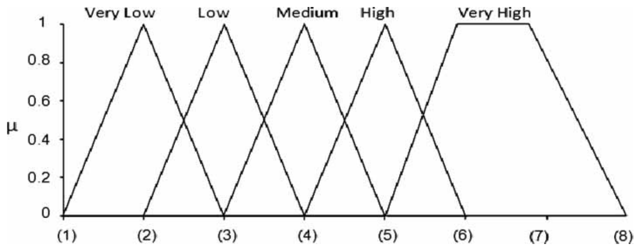
Pressure adjustment

Pressure is the most important factor that influences the leakage flow rates and other leakage influencing factors (Farley 2001). To model the relationship between pressure and other influencing factors, a PAF has been proposed to reflect the influence of pressure to all pressure dependent

Table 1 | Fuzzy sets and linguistic definition of input parameters



Reference Figure: T1



Reference Figure: T2

Inputs	Symbol	Interval	Ref. Fig.	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
LD	$X^4_{1,1}$	0–300	T1	0	0	150	300	300	300		
FL	$X^4_{2,1}$	0–30000	T1	0	0	15000	30000	30000	30000		
CD[1]	$X^4_{3,1}$	5–0	T1	0	0	0.9	2	5	5		
ST[2]	$X^4_{4,2}$	0–100	T1	0	0	30	60	100	100		
TF	$X^4_{5,2}$	0–20	T1	0	0	6	12	20	20		
GF	$X^1_{6,2}$	0–10	T1	0	0	3	6	10	10		
NM	$X^4_{9,2}$	0–100	T1	0	0	30	60	100	100		
NS	$X^4_{10,2}$	0–100	T1	0	0	30	60	100	100		
NJ	$X^4_{11,2}$	0–50	T1	0	0	15	30	50	50		
RD[3]	$X^4_{12,3}$	0–1	T1	0	0	0.5	1	1	1		
CoD	$X^4_{13,3}$	0–1	T1	0	0	0.5	1	1	1		
InD	$X^4_{14,3}$	0–1	T1	0	0	0.5	1	1	1		
PP	$X^4_{14,2}$	0–1	T1	0	0	0.5	1	1	1		
BB	$X^4_{15,2}$	0–1	T1	0	0	0.5	1	1	1		
C	$X^4_{16,2}$	0–1	T1	0	0	0.5	1	1	1		
PM	$X^4_{7,1}$	0–1	T1	0	0	0.5	1	1	1		
PD	$X^4_{8,1}$	0–10	T1	0	0	0.3	0.72	10	10		
SP	$X^3_{1,2}$	0–100	T2	0	0	25	50	75	100	100	100
HL	$X^3_{2,2}$	2–0	T1	0	0	0.25	0.5	2	2		
PA	$X^3_{1,4}$	0–100	T2	0	0	25	50	75	100	100	100
IA	$X^3_{2,4}$	0–100	T2	0	0	25	50	75	100	100	100

[1]Cover depth and head loss has reverse relationship with LP. Therefore, in Figure T1 the 'Low' should be read as the 'High' and the 'High' should be read as the 'Low'.
[2]Soil type defined by percentage finer than 0.002 mm.
[3]All the demands are relative to pressure drop. If pressure drop due to demand is high, then demand is considered as a high value and vice versa.
[4]Low placement quality considered when pipe placement is carried out by unskilled technicians with no engineering supervision and high placement quality when placement is carried out by skilled technician with engineering supervision. Same is considered for Bedding and Backfills and for Compaction.
[5]Assumed low value for metallic (DI, ST,GI, CI, etc.) pipes, medium value for plastic (HDPE, PE, PVC, etc.) pipes and high value for others (PC, AC, etc.) pipe materials.
LD = Traffic loading (KN); FL = Traffic flow (Vehicle/h); CD = Cover depth (m); ST = Soil type (% finer); TF = Temperature fluctuation (°C); GF = Ground water table fluctuation (m); NM = (Number of) water meters; NS = (Number of) service connection; NJ = (Number of) joints; RD = Residential demand; InD = Industrial demand; CoD = Commercial demand; PP = (Quality of) pipe placement; BB = (Quality of) bedding and backfills; C = Quality of compaction; PM = Pipe materials; PD = Pipe diameter (m); SP = System pressure, m; HL = Head loss (m/km); PA = Pipe age (yr); IA = Network instrument age (yr).

basic inputs. If ρ_G^{G-1} is the output for the influencing factors of the generation Gth, ρ_G^{G-1} will serve as input for the upper generation, i.e. generation $G^{\text{th}-1}$. The proposed PAF has been applied to the outputs (ρ_G^{G-1}) under the condition of (ρ_G^{G-1}) × PAF ≤ 1. The influence of pressure propagates to the final crisp LP according to their relationship in Figure 1.

There are three main steps to calculate the proposed PAF. Firstly, it is necessary to select the 'reference system pressure' and operating system pressure. The term 'reference system pressure' is the pressure above which leakage and break frequency increases more rapidly. At this level, pressure initiates to influence the other leakage influencing factors. For a system with continuous supply, leakage and break frequency increases rapidly when pressure exceeds around 35–40 m (50–57.1 psi) of head (Lambert 2001; Farley & Trow 2003). Therefore, a reference system pressure could be between 35 and 40 m (50–57.1 psi) of head. However, the value of reference system pressure could change based on the network condition, age of network, design standards and other factors.

The average operating system pressure should be calculated as an average of upstream and downstream pressure of the pipe if the proposed model is intended to apply to an individual pipe. However, if the model intended to apply to a whole or part of WDS, then average operating system pressure should be selected in such a way that it represents the average operating system pressure of the whole or part of WDS, respectively.

Secondly, it is necessary to estimate the pressure exponent (N1) which generally varies between 0.50 and 2.50, depending upon the type of the leakage path, network age, corrosion, materials and other network related factors (Farley & Trow 2003). This parameter can be estimated using zero pressure step test (Islam & Babel 2012).

Finally, this research developed a special FRB model based on the approach discussed above under Fuzzy rule-based modeling. For this special model, pressure is considered to be the only influencing factor and hence the defined rules for this model is only pressure dependent. For example, if pressure is *low* then LP is *low*; if pressure is *high* then LP is *high*.

The model has been then used to determine LP for estimated reference system pressure (LPRP) and LP for estimated operating system pressure (LPSP). Based on estimated LPRP, LPSP and pressure exponent N1, PAF is calculated by using Equation (3):

$$PAF = \left(\frac{LPSP}{LPRP}\right)^{N1} \quad (3)$$

The relationship of Equation (3) is based on the general relationship between pressure and leakage. According to Lambert (2001) the appropriate relationship between leakage and pressure can be expressed by the following two equations:

$$L \, \alpha \, P^{N1} \quad (4)$$

$$\frac{L1}{L0} = \left(\frac{P1}{P0}\right)^{N1} \quad (5)$$

where L represents the leakage volume per unit time, P represents the pressure, P_0 is the reference system pressure, L_0 is the leakage rate for the reference system pressure, P_1 is the system pressure at any time, L_1 is the system leakage for Pressure P_1 and N1 is the pressure exponent.

APPLICATION OF PROPOSED MODEL

The proposed model can be implemented to an individual pipe, or to a part of WDS or to a whole WDS. The extent of application depends on the degree of accuracy required for a particular case and spatial variability of the influencing factors. If the spatial variability of different leakage influencing factors is very high, the developed model should be implemented in each pipe of the network. In this case, each pipe will have a separate LP and these can be presented as an LP map of WDS. However, if the spatial variability of different leakage influencing factors is relatively small, the developed model can then be implemented in the network as a whole and therefore a crisp value of the LP will be evaluated for the whole WDS.

Case study – Bangkok's metropolitan water authority

To evaluate the practicality of this research, the model has been implemented in a small district metering area (DMA) of the Metropolitan Water Authority (MWA) of Bangkok (Thailand). The MWA water supply system consists of 15 service areas with 14 branch offices and one separate office in charge of the water provision, customer services, pipe and valve repairs, meter replacement, meter recording, bill collection and other related services (MWA 2005). The study DMA is located at Bangkoknoi branch which operates about 1,200 km of pipe network. Figure 2 shows the network layout for the DMA-00144 (Islam 2005).

The DMA is comprised of an inlet (entry of water from the large network) and 60 pipes with a total length of 17.5 km connected by 77 junctions and 19 different types of valves. Additional basic information about the study area is presented in Table 2. About 50% of the pipe materials in the case study network are polyvinyl chloride (PVC), while 41% are asbestos cement (AC). The percentage of metal pipes, steel (ST), galvanized iron (GI) and cast iron (CI) are around 10% (Islam 2005). The following section provides more detailed information on the case study and its background.

Data collection

Most of the information required can be extracted from a well developed and calibrated network hydraulic model. However, for this study, the necessary information was collected from MWA, Bangkoknoi office.

The average operating system pressure during the night time is very low compared to the operating system pressure at day time. A 3 day (1–3 September 2004) average night time (00:00 am to 01:00 am) minimum operating system pressure was as low as 4.47 m (6.39 psi), however, the average day time (12:00 to 13:00) maximum operating system pressure was 18.76 m (26.80 psi). The average operating system pressure for the period of 1–3 September 2004 was 12.56 m (17.94 psi). A considerable seasonal variation of the operating system pressure exists (Islam & Babel 2012). However, this research evaluates the LP based on an average operating system pressure (i.e. 12.56 m) during 1–3 September 2004.

This study assumed a reference system pressure for the network as 25 m (35.71 psi). The value of pressure exponent, N1 has been estimated using a pressure step test. From the pressure step test, the estimated value of N1 for the study area is 1.16 (Islam 2005). (Details of N1 calculation is out of scope of this study. However, it could be obtained from the first author on request.)

The study area DMA is located in a residential area in the southern part of Bangkok where traffic flow and loading are not heavy. Consequently, a medium traffic loading and traffic flow has been considered. Cover depth and different types of workmanship of each pipe has been also estimated based on site working experience in the area.

Bangkok has predominantly clay soil (Salokhe & Ramalingam 2001). Around the year, the temperature and ground water table fluctuation is not very high. The study area is located in a residential zone where industrial and commercial water demands are lower compared to residential water demand. Table 2 provides information for the

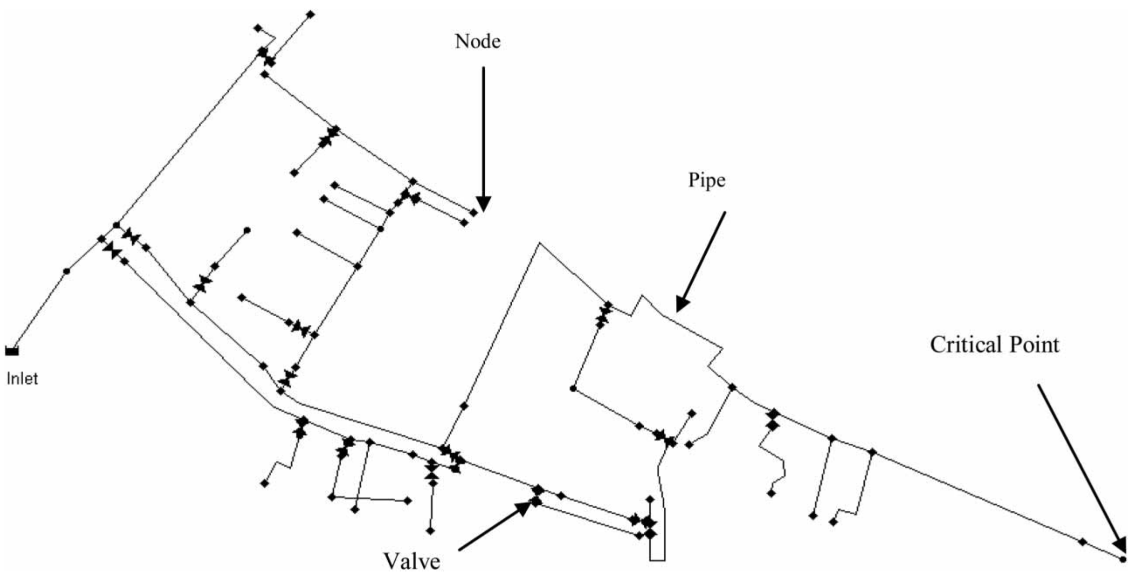


Figure 2 | Network layout for DMA-00144.

Table 2 | Study area at a glance

Actual data	Value
Area coverage	2.5 km^2
Population served (estimated)	3570
No. of metered properties	820
Total pipe length	17.5 km
Average daily pressure (Sept' 04)	12.56 m (17.94 psi)
Non revenue water, May 2004	37.30%
Maximum diameter of the pipe	300 mm
Pressure exponent	1.16
Major pipe materials	PVC, AC

study area which has been collected from MWA, Bangkoknoi office. Table 3 shows values for all 24 factors that are used to model LP for the study area. These values are based on Table 2 and the site working experiences with a project for MWA, Bangkoknoi office.

Results

The DMA-00144 is a very small area (2.5 km^2). The head loss from inlet point to most critical point (where pressure is minimal than any part of the network at all times) is less than 0.5 m (Islam 2005). Moreover, detailed information about each component of the network is not easily available. Therefore, the research assumed that the whole study DMA has similar characteristics (i.e. similar cover depth, traffic flow, traffic loading, temperature variation, reference pressure, pressure exponents, age, etc. for all pipes and network components) and average operating system pressure

Table 3 | Data used for the modelling of LP for the study area

Parameter number	Parameter name	Symbol	Unit	Modeled mean value	Standard deviation	Source
1	Traffic loading	LD	KN	70	17.5	A
2	Traffic flow	FL	Veh./hr	3000	750	A
3	Cover depth	CD	M	0.6	0.15	A
4	Soil type	ST	% finer	30	7.5	SR, A
5	Temperature fluctuation(ground)	TF	0C	1	0.25	A
6	Groundwater table fluctuation	GF	M	1	0.25	A
7	Pipe materials	PM	None	0.4	0.1	I,A
8	Pipe diameter	PD	Mm	300	75	I
9	Number of water meter	NM	No./km	47	11.75	I
10	Number of service Connection	NS	No./km	47	11.75	I
11	Number of joints	NJ	No./km	10	2.5	A
12	Residential demand	RD	None	0.3	0.075	A
13	Commercial demand	CoD	None	0.6	0.15	A
14	Industrial demand	InD	None	0.6	0.15	A
15	Pipe placement	PP	None	0.3	0.075	A
16	Bedding and backfills	BB	None	0.3	0.075	A
17	Compaction	C	None	0.3	0.075	A
18	Network instrument workmanship	NIW	None	0.3	0.075	A
19	Reference system pressure	RP	M	25	6.25	A
20	Pressure exponent	N1	None	1.16	0.29	I
21	System pressure	SP	M	12.56	3.14	I
22	Head loss	HL	m/km	0.4	0.1	I
23	Pipe age	PA	Year	25	6.25	I
24	Network instrument age	IA	Year	25	6.25	I

A = Assumed data based on site working knowledge; I = Islam (2005); SR = Salokhe & Ramalingam (2001).

represents the system pressure of the whole study DMA. Consequently, the model has been applied as a whole to the DMA and the estimated LP represents the study area as a whole.

Using the proposed model, for current operating system pressure the estimated LP for DMA-00144 of Bangkoknoi office is 49%. An LP of 49% indicates that in the current situation, if no leakage reduction or control measures are taken then 49% of inflow would be lost due to leakage. It can be noted that the calculated LP and estimated leakage rate are not the same. The calculated LP from a distribution network will not change based on short-term leakage control and reduction activities. However, leakage volume varies with the change of short-term leakage reduction and control activities. It is expected that the estimated LP will always be higher than or equal to current leakage rate.

Although 24 factors are identified contributing to LP, some of the factors have a major influence whereas others' influences are minor. It is identified (Figures 3 and 4) that in a certain range, the operating system pressure and age of the network are the most important factors to contribute to LP. To observe the impact of pressure, LP has been estimated for various system pressures while all other factors remain constant.

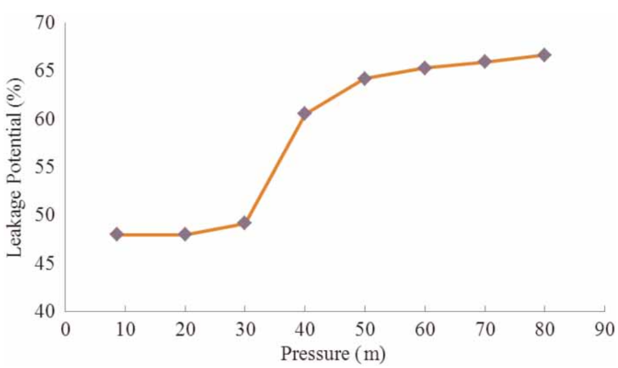


Figure 3 | LP with age for two different operating system pressures.

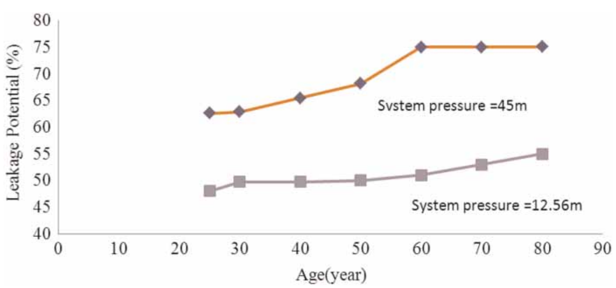


Figure 4 | LP with age for two different operating system pressures.

Figure 3 shows that, for the existing network condition, for an operating system pressure less than 30 m (42.86 psi), the network LP is not very sensitive to pressure. However, when pressure exceeds 30 m (42.86 psi), the network LP is more sensitive to the operating system pressure. As stated earlier, the current average operating system pressure in the study DMA is 12.56 m (17.94 psi). This value is very low compared to pressure in any European or North American WDS. For example, the median of average operating system pressure in England and Wales is 42 m (60 psi) (Farley & Trow 2003). Figure 3 also shows that after 60 m (85.71 psi) of pressure, the rate of change in LP is relatively small. This is mainly because the WDS will be almost in failure state if the system approaches that level of pressure and age. Similar analysis has been carried out for various ages of network keeping all the other factors unchanged. From Figure 4, it appears that the impact of age to LP is very gradual for the current operating system pressure of 12.56 m (17.94 psi). However, if the operating system pressure increases to 45 m (64.29 psi), LP will increase more noticeably for same age combination (Figure 4). Additionally, Figure 4 reveals that for higher operating system pressure, LP is more sensitive in the age range of 30 to 60 years. This also indicates that the network will be virtually unusable after 60 years as the LP will be very high.

Sensitivity analysis

To evaluate the impacts of different uncertain parameters (modeled factors are termed as parameters, however, in some cases parameters and factors have been used interchangeably), Monte Carlo (MC) simulation ($\varepsilon = 1.5\%$, $n = 2000$) and Spearman rank correlation coefficients based sensitivity analysis have been carried out. Three scenarios have been investigated.

The uncertainties in the identified parameters have been modeled by assigning a probability distribution to each input factor/parameter. The research applied a normal distribution for all basic factors. The means and standard deviations of all parameters have been assumed based on estimated and/or observed value. Due to lack of data, standard deviations for each factor has been assumed as 25% of the mean as assumed for demand multipliers by Torres *et al.* (2009).

The impacts of uncertainties of each factor/parameter are related to the estimated value of parameters or factors, not general for all ranges of values of parameters. The estimated factors might be more or less sensitive in a certain range of their values. For example, LP is less sensitive to an operating system pressure when it is less than 30 m (42.86 psi). The sensitivity becomes more considerable when operating pressure is greater.

The Spearman rank correlation coefficients have been calculated by using Equation (6) (Walpole *et al.* 2007):

$$r_s = 1 - \frac{6}{n(n^2-1)}\sum_{i=1}^{n} d_i^2 \qquad (6)$$

where, $i = 1, 2, 3 \ldots n$; n is the number of pairs of data (number of iterations) and d is the difference between the ranks of the ith value of input parameter and the corresponding LP value.

Scenario I

As stated earlier, the most influencing factors for LP are pressure (e.g. reference system pressure, pressure exponents, head loss and operating system pressure) and network age (e.g. age of the pipe, age of the network instruments). To see the impacts of other factors, in this scenario, MC simulation has been carried out excluding the most influencing factors.

Figure 5 presents: (a) probability distribution function (PDF) and cumulative distribution function (CDF); and (b) Spearman ranks correlation coefficients. Figure 5(a) shows that LP is not very sensitive and most of the iterations calculated LP around 49%. Figure 5(b) shows that cover depth and traffic loading are the most influencing factors. It is industry practice to respect a minimum cover depth of 1.2 m for a buried pipe. If this cover depth decreases while traffic loading and traffic flow increase, the risk of pipe failure will increase significantly. Therefore, traffic loading is positively correlated whereas cover depth is negatively correlated. For the study network, the assumed mean cover depth and standard deviation is 0.6 and 0.15 m, respectively. The small cover depth makes the network extremely vulnerable against traffic impact. However, if the covered depth was more than 1.2 m, then the cover depth and loading would not be that sensitive. After the traffic factors, the workmanship parameters are the next sensitive factors. This research studied four workmanships factors (e.g. pipe placement, bedding backfilling, compaction and workmanship for network instruments).

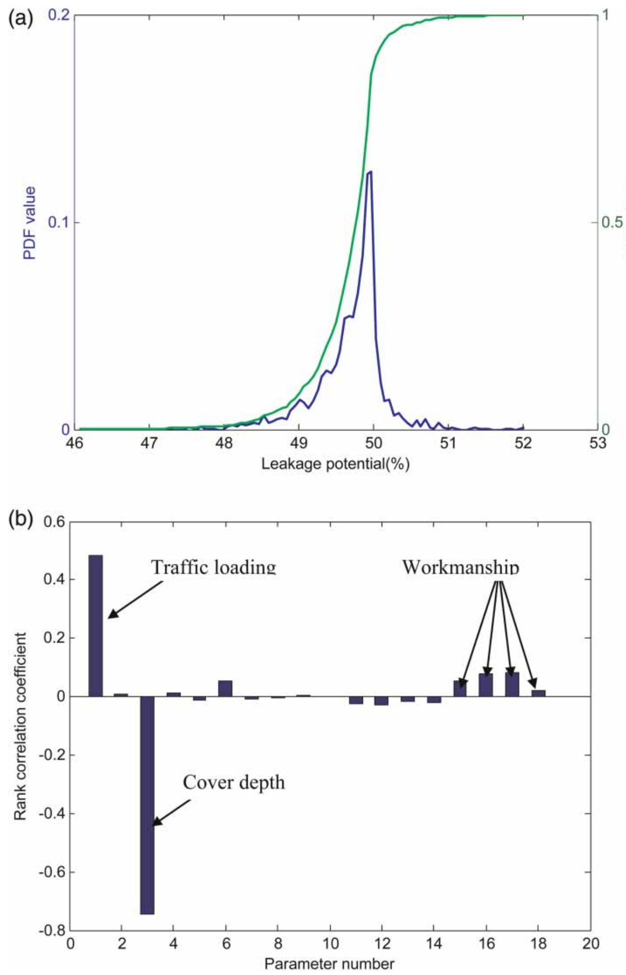


Figure 5 | MC simulation results for Scenario I (a) PDF and CDF (b) Spearman rank correlation coefficients.

Scenario II

For Scenario II, MC simulation has been carried out considering all factors as varied. Figure 6 shows that the shapes of PDF and CDF have not changed significantly as compared to Scenario I. However, an additional small peak is observed in PDF curve indicating less sensitivity of LP

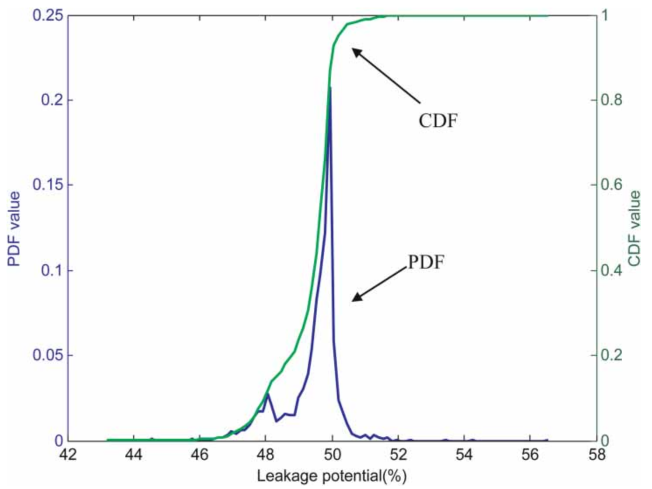


Figure 6 | MC simulation results for Scenario II: PDF and CDF.

against the low operating system pressure. Note that, as Figure 3 indicates, LP is not very sensitive to operating system pressure below 30 m. Nevertheless, the network might behave quite differently if the operating system pressure increased to a range 30–60 m as shown in Figure 3. On the other hand, Figure 4 suggests that at the age of under 60 years, for low pressure (e.g. 12.56 m or 17.94 psi) and under 30 years, for high pressure (e.g. 45 m or 64.29 psi), LP is not very sensitive to the age of the network (i.e. the age of the pipes and age of the network components). The estimated leakage potentials for these two cases are around 50 and 62%, respectively.

From the Spearman rank correlation coefficients, it reveals that the age of the pipe becomes more sensitive than cover depth. In addition to the impact of the network age, the cover depth and traffic loading are the most critical influential factors.

Scenario III

In this scenario, MC simulation has been carried out considering all parameters as variable and operating system pressure and age of the network has been increased to 45 m (64.29 psi) and 35 years, respectively. Similar to previous scenarios, Figure 7 shows: (a) PDF and CDF and (b) Spearman rank correlation coefficients. It is observed that due to increase of age, the value of PDF has increased towards the highest range of LP. This indicates that if the network age is around 35 years and the operating system pressure is 45 m, the network will be virtually unable to deliver water to the customers. As in scenario II, Figure 7(b) reveals that the operating system pressure and pressure related factors are the most influencing factors followed by the age of the pipe.

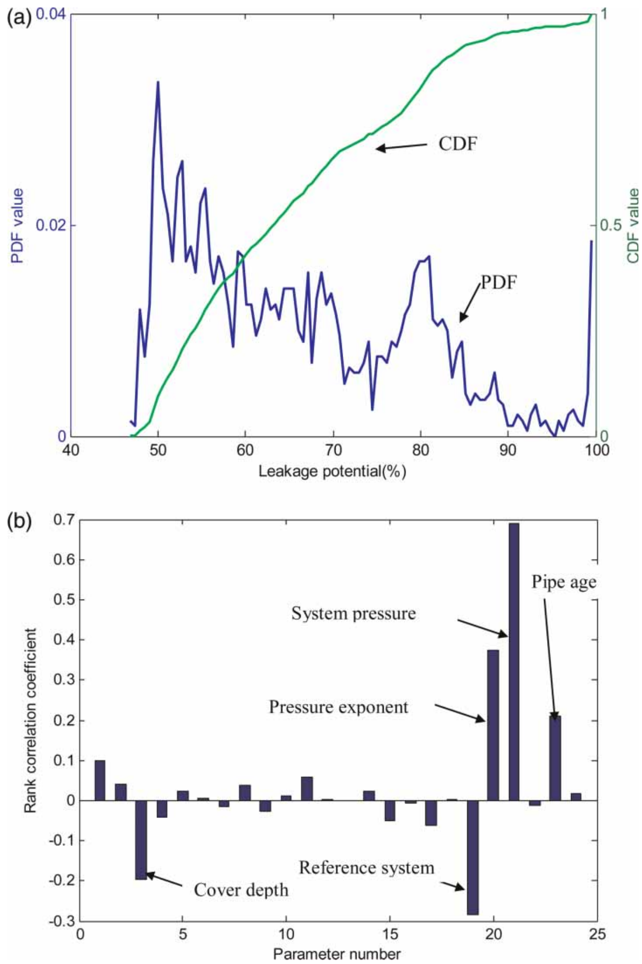


Figure 7 | MC simulation results for Scenario III (a) PDF and CDF (b) Spearman rank correlation coefficients.

CONCLUSIONS

This research has developed an FRB model to estimate LP for WDS identifying various key leakage influencing factors. A normalization method has been adopted which will simplify the interpretation of the FRB modeling results to the non-technical people. Additionally, a new adjusted FRB methodology has been proposed to adjust the impact of such factors which can also influence other contributory factors.

Detailed sensitivity analysis revealed that the operating system pressure and pressure related factors such as reference system pressure and pressure exponent are the most influencing factors. The results also confirmed that after pressure related factors the pipe age is the most important factor. However, the sensitivity of these factors varied according to the range of operating system pressure and network age. It is also identified that the cover depth of the pipe is very influential in a certain range. However, cover depth is less pressure dependent. The next influencing factors are different kinds of workmanship of the network and network components. It is noted that among 24 factors around half (e.g. pressure related factors, age, workmanships, cover depth) of them are most influential on LP and the remaining half (e.g. ground water table fluctuation, head loss, soil type) have minimal influence.

Though this model has been applied to a network of low pressure, the model can be used for any network by modifying appropriate factors/parameters. Indeed, the model should be updated based on any specific condition of any particular network, especially ranges of different influencing factors. Moreover, the developed methodology can be extended to other similar problems. In the case study, some of the data have been estimated based on the information collected from state-of-the practice, manuals and the experiences in the study area. However, by collecting those data, estimated LP would be more accurate. In spite of the limitation, the proposed methodology is capable of helping water utility managers to prioritize their leakage control and rehabilitation policy through better understanding of their network.

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