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Estimating Risk of Contaminant Intrusion in Distribution Networks Using Fuzzy Rule-Based Modeling

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Abstract. Contaminant intrusion is one of the main causes for post-treatment water quality failure. Three conditions need to exist for contaminant intrusion to occur: a pathway, a source of contamination and a driving force. Intrusion pathways can be provided by compromised components of the water mains, including broken or leaky pipes, corrosion pinholes, faulty or deteriorated gaskets, etc. Compromised sewers in close vicinity and contaminated soil (and ground water) around pipes can become a source of contamination, as can any non-potable fluid system that is connected to the water supply system (cross-connection) without proper protection. Situations in which the pressure at a contaminant source is higher than that inside the water network will constitute a driving force. Such situations can occur during maintenance and repair events - when pipes are de-pressurised, during transient pressure events such as abrupt pumps shut downs or fire extinguishing events, and cross-connections where the pressure is higher in the non-potable system (e.g., car wash stations).

The rarity of water quality failures belies their seriousness, as some of these failures have the potential to inflict harmful public health effects and increase public mistrust and complaints. In such data-sparse circumstances, expert knowledge and belief can serve as an alternative representation of a domain. In this paper, a soft computing model is presented to quantify the risk of contaminant intrusion. The proposed model uses a directed acyclic cognitive map; where causal relationships are established using fuzzy rule-based modeling. The fuzzy rules are defined based on expert judgments and beliefs. The application of the proposed method is demonstrated with the help of a hypothetical example.

Keywords. Fuzzy rule-based modeling, contaminant intrusion, water distribution networks, risk, and uncertainties

1. Introduction

Water quality in a distribution network can be described by specific microbiological, physico-chemical and aesthetic attributes of water. In a well-maintained water supply system these attributes are kept in a desirable range, predefined by upper and/or lower limits. Each water quality attribute encompasses a number of water quality indicators. The overall acceptability of water quality for its intended use depends on the magnitude of these indicators and is often governed by standards and guidelines (or self imposed limits). A ‘water quality failure’ is defined as a violation of these standards and guidelines of one or more water quality indicators [8].

Six mechanisms/pathways can lead to water quality failures in distribution networks, namely, contaminant intrusion, microbial regrowth, contaminant breakthrough, internal corrosion, leaching and permeation. Of the six, five mechanisms (breakthrough is the exception), are directly affected by pipes, either through pipe material type, size, structural condition, hydraulic / operational conditions and/or inner surface degradation [8]. Table 1 shows a relative frequency (1971-1998) of deficiencies attributed to the outbreaks of illness that were traced to distribution networks [6]. Environmental conditions such as the quality of the raw water, temperature and soil conditions around pipes can also have a direct or indirect impact on fluctuations of water quality in distribution networks [3].

Table 1. Deficiencies in distribution networks resulting in documented outbreaks of waterborne illness in the USA from 1971-1998 [6]

Cited deficiency causing illness outbreak	# of events	% of total	Intrusion pathway	Pressure	Contamination source
Cross-connection and back siphonage	60	53.1	✓	✓	✓
Inadequate separation of water main and sewer	1	0.9	✓	✓	✓
Broken and leaky water mains	10	8.8	✓	✓	✓
Contamination in storage	15	13.3	✓		✓
Contamination during construction/repair	6	5.3	✓		✓
Contamination of household plumbing	8	7.1			✓
Metal corrosion and metal leaching	13	11.5			✓
Total	113	100			

The deterioration of pipe structural integrity can have a multi-faceted impact on water quality, especially in the domain of contaminant intrusion. Frequent pipe breaks increase the possibility of intrusion through compromised sections in several ways. During repairs, contamination can occur if flushing and local disinfection procedures are not appropriately followed. This low pressure induced in the pipe during its repair (de-pressurizing) increases the potential of contaminant intrusion through unprotected cross connections. If the pipe has holes then de-pressurization will increase the likelihood of contaminant intrusion, which can be especially detrimental if the surrounding soil is contaminated by leaky sewers, chemical spills, herbicides, pesticides, etc.

This paper presents a method that uses fuzzy sets to quantify the risk of contaminant intrusion at a given location in a water distribution network. The remainder of the paper is organized as follows: next section provides an introduction to the mechanisms of contaminant intrusion in distribution water mains. The background and formulation of the proposed fuzzy-based method is presented in the following section. It is then followed by an application of the proposed method to contaminant intrusion in the distribution network. Finally, results and conclusion of the paper are presented.

2. Contaminant Intrusion

Intrusion of contaminants (hitherto referred to simply as “intrusion”) into the water supply system can occur through pipes and storage tanks (animals, dust-carrying bacteria, infiltration). Intrusion through deteriorated water mains can occur during maintenance and repair events, through broken pipes and gaskets, and cross-connections. Kirmeyer *et al.* [3] ranked pathogen (contaminant) entry routes into the distribution network based on responses from an expert panel, the members of which were instructed to identify and rank the importance of routes of entry. Results, summarized in Table 2, indicate that risk associated with intrusion was rated mostly "high". In addition to pathogens, intrusion can also introduce chemicals, such as pesticides, herbicides, hydrocarbons (gasoline spills) as well as physical contaminants, such as plant debris and soil particles. Intrusion into water mains requires the simultaneous presence of three elements, a pathway, driving force and a contamination source. Brief descriptions of these elements are provided in following sub-sections.

Table 2. Microbial risk in the water supply system - routes of entry (modified after [3])

Route of entry	Priority/risk level
Water treatment breakthrough	High
Transitory contamination (intrusion)	High
Cross connection (intrusion)	High
Water main repair/break (intrusion)	High
Uncovered storage facilities (intrusion)	Medium-High
New main installations (intrusion)	Medium
Covered storage facilities (intrusion)	Medium
Growth/re-suspension	Low
*Purposeful contamination (deliberate intrusion)	No

*After the recent terrorist activities, the purposeful contamination might be rated as a higher-level risk.

2.1. Pipe Breakage / Repair and Cross-connection – Pathway

A water distribution network can never be completely water tight due to the existence of pipe cracks, holes, faulty gaskets and/or faulty appurtenances, which can serve as intrusion pathways. The driving force required for intrusion is usually a pressure differential. It is improbable that intrusion will occur as long as the water pressure inside the network is greater than the pressure outside although movement of microbial or viral contaminants against the pressure gradient is theoretically possible, though not documented. Pressure differential can occur during maintenance activities, such as during break repair, flushing, etc., when parts of the distribution network are de-pressurized. Sources of contaminants include sewage water ex-filtrated from adjacent broken sewers, contaminated groundwater/soil and backflow through unprotected cross-connections.

Another direct pathway of intrusion is the actual exposure of a broken pipe to contaminated soil or water during repair. Contamination may propagate if proper flushing and disinfection procedures are not followed prior to re-commissioning. Clearly, the frequency of pipe breakage, the duration of repair jobs and the size of the network segment that can be isolated during maintenance are factors that have an impact on the risk of intrusion.

Cross-connection is a term used to describe a physical link through which it is possible for a non-potable liquid to enter into a potable water distribution network. Typically, when the pressure in the non-potable system is greater than that in the water distribution network, the existence of an unprotected cross-connection may result in the backflow of contaminants into the potable water supply system.

2.2. Transient Pressures – Driving Force

In addition to pressure differentials arising due to de-pressurization of pipes, as discussed earlier, extreme transient pressures can also cause pressure differentials. Extreme transient pressures in a water supply system can occur as a result of power failure in a pumping station, fast closure of valves, fire flows, pipe rupture, etc. These transients can cause negative pressures in pipes, which sometimes may be exacerbated by peculiar topographical conditions. These negative pressures may provide a driving force for contaminants to intrude through compromised pipe walls and joint gaskets. Extreme transient pressures are more likely to occur in long transmission mains than in an urban distribution network in which users' faucets effectively serve as widely distributed pressure relief valves. An exception may be during fire flows or in the vicinity of a wet industrial facility. The volume of the inflow of the contaminated solute is typically quite small (less that 1% of the flow in the pipe) since the duration of transient pressures is typically quite short [3].

2.3. Sources of Contamination

Contamination sources can be either chemical (pesticides, herbicides, petroleum products, fertilizers, solvents, detergents, pharmaceuticals, etc.) or microbiological (microbes, viruses, bacteria). Karim *et al.* [1] reported concentrations of total coliform, fecal coliform, clostridium, bacillus, and viruses in soil and water samples taken around water mains. Total and fecal coliforms were found in more than 60% and 40% of the samples, respectively. Bacillus was found in most of the samples, as was expected, because it is a natural soil organism. Enteroviruses, Norwalk and Hepatitis A viruses were also found around pipes, giving a strong indication of human and animal sources of contamination. Karim *et al.* [1] also reported the range of concentrations for various organisms found in soil samples collected in the vicinity of the water mains.

Intrusion is a complex phenomenon, which depends on above three elements but generally data on these elements are incomplete, vague and uncertain. Fuzzy-based methods provide a meaningful way to use these data to make inferences on the risk of contaminant intrusion. The next section provides a background of fuzzy-based methods and its application to assess the risk of contaminant intrusion in distribution networks.

3. Fuzzy-based Method

Fuzzy cognitive map (FCM), an extension of cognitive map, is an illustrative causative representation of the description and model of complex systems [5]. FCM draws a causal representation among all identified factors or concepts of any specific system. A complex system represented by FCM can incorporate human experience, understanding and knowledge of the system.

FCM consists of nodes (factors, concepts) and weighted arcs (causal strength, connection, edge), which are graphically illustrated as signed weighted graph(s) with optional feedback loops. Nodes on the graph represent concepts describing behavioural characteristics of the system. Concepts can be inputs, outputs, variables, states, events, actions, goals, and trends of the system. Signed weighted arcs represent causal relationships that exist among concepts.

Traditionally, causal connections in FCMs are used to describe relationships in a forward-inferencing and monotonic ways [2]. For example, if there is a positive causal link of certain strength (w_{ij}) between a causal node C_i and effect node C_j, the state value A_j will increase (decrease) with any increase (decrease) in the state value A_i. In rule-based modeling framework this concept can be translated into fuzzy rules. For example, negative causality (monotonically decreasing) can be represented by fuzzy rules such as: "*If* C_i is *high* (*low*, *medium*) *then* C_j is *low* (*high*, *medium*)" (equivalent to $w_{ij} < 0$ in traditional FCM). Conversely, positive causality (monotonically increasing) can be represented by fuzzy rules such as: "*If* C_i is *low* (*high*, *medium*) then C_j is *low* (*high*, *medium*)" (equivalent to $w_{ij} > 0$ in traditional FCM). However, real-world problems are often non-monotonic, which cannot always be dealt with by traditional FCMs, but could be efficiently handled through fuzzy rule-based relationships [2]. For example, non-monotonic causality can be represented by fuzzy rules such as: "*If* C_i is *low* (*high*, *medium*) then C_j is *low* (*low, medium or high*)".

Fuzzy rule-based modeling (FRBM) can be used to make inference in FCMs either through the use of aggregation (weighting) of single-input-single-output (SISO) or through multiple-inputs-single-output (MISO) fuzzy models. Inferencing through SISO model cannot capture effectively the co-occurrence of multiple causes such as "if *A* **and** *B* then *C*". On the other hand, MISO models, which can capture co-occurrence of multiple causes, can also become extremely complex because of dimensionality issues. However, by introducing dummy nodes this dimensionality can be reduced.

In FRBM, the relationships between variables are represented by means of fuzzy *if-then* rules of the form "*If antecedent proposition then consequent proposition*". The antecedent proposition is always a fuzzy proposition of the type "*X is A*" where *X* is a linguistic variable and *A* is a linguistic constant term. The proposition's truth-value (or membership value), which is a real number $\in$ [0, 1], depends on the degree of similarity between *X* and *A*. This linguistic model [7] has the capacity to capture qualitative and imprecise/uncertain knowledge in the form of *if-then* rules such as

$$R_{i\,j}\text{: } \textbf{\textit{If}}\ X \text{ is } A_i\ \textbf{\textit{then}}\ Y \text{ is } B_j \qquad i = 1, 2, \ldots, L; \quad j = 1, 2, \ldots, N$$

where $R_{i\,j}$ is the rule number (in a rule set Rm), *X* is the input (antecedent) linguistic (fuzzy) variable and A_i is a fuzzy subset, which corresponds to an antecedent linguistic constant (one of *L* in set *A*). Similarly, *Y* is the output (consequent) linguistic (fuzzy) variable and B_j is a fuzzy subset, which corresponds to a consequent linguistic constant (one of *N* in set *B*). A fuzzy rule can be regarded as a fuzzy relation, i.e., simultaneous occurrence of values *X* and *Y*.

Consider an effect node "*B*" which is connected to two causal concepts "*A*" and *C*". A graphical representation of the causal relationships is shown in Figure 1. The "AND" sign represents that both "*A*" and "*C*" are required for "*B*" to occur. The details of this two-input MISO model are graphically shown in Figure 2. The process is shown in three distinct steps, namely, fuzzification, inference (a rule base and inference engine) and defuzzification [7]. Assume that causal concepts *A* and *C* are activated at levels of $A' = 0.4$ and $C' = 0.6$, respectively. The rule-base consists of 6 rules (3 × 2) and input activation signals (A') and (C') fire first 4 rules to predict output B' which is defined over the universe of discourse *Y*. The procedure described in Figure 2 is used to make inference from the rule-base. The defuzzification method described in Figure 2 uses quality ordered weights (q_k) for every subset B_k. These weights are simply multiplied to corresponding output fuzzy set $\mu_{B_k}(y)$ and a weighted score is the defuzzified value B'. The details of the notations used in Figure 2 can be found in [7] and [5]. The crisp value approximates the deterministic characteristics of the fuzzy reasoning process based on the output fuzzy set, which helps to convert the uncertainty into an applicable action when solving real-world problems.

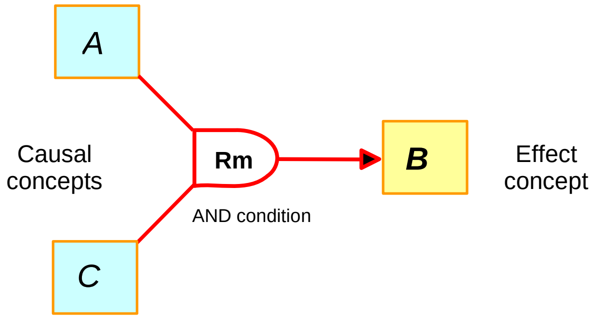


Figure 1. Two causal concepts (*A* and *C*) connecting to an effect concept (*B*)

4. Estimating Risk of Contaminant Intrusion

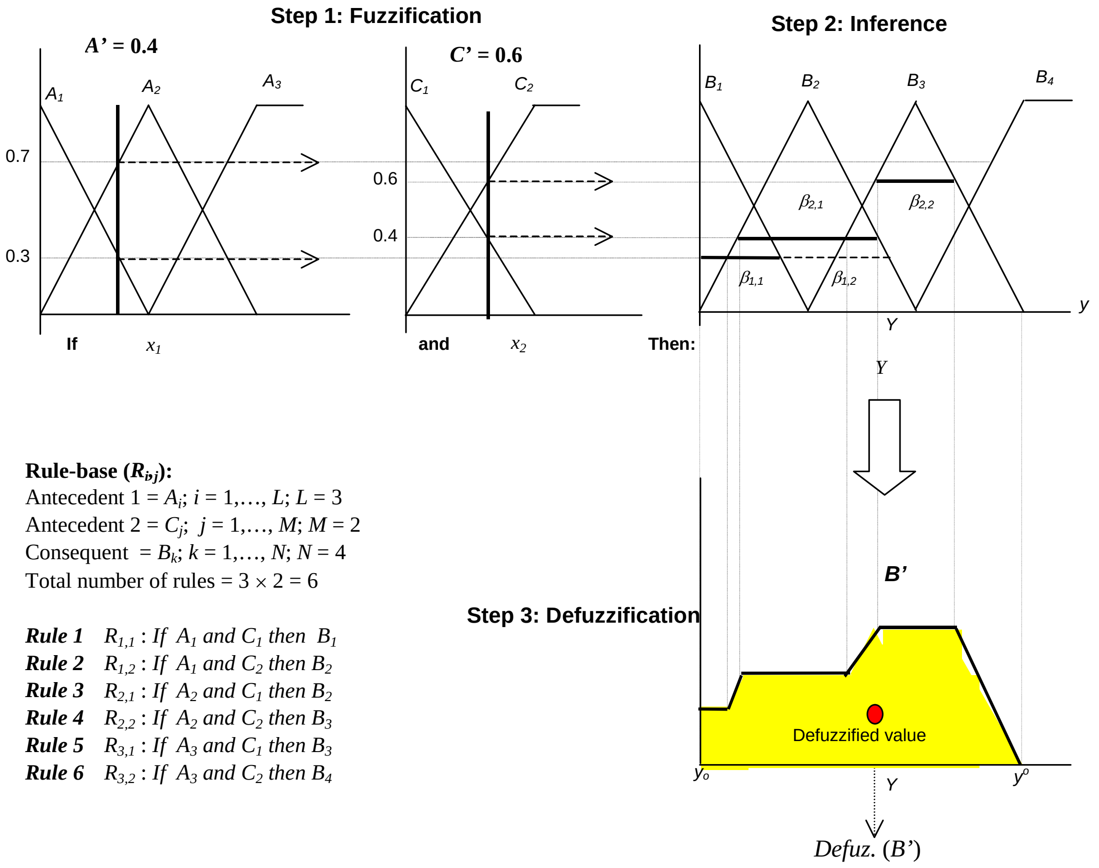
Figure 3 shows the FCM for estimating the potential for contaminant intrusion in a given pipe segment of distribution network. The causal relationships are described using fuzzy rule-sets described by Rm. For example, if there are three causal concepts (antecedents) feeding into an effect concept and each causal concept is defined at three levels (e.g., *low*, *medium* and *high*), then total of 27 rules are required to make an inference for an effect concept. To reduce the dimensionality of the rules in a rule set Rm, dummy nodes (concepts/factors) can be introduced, when the number of causal concepts exceeds 3. The following 6-step procedure is adopted to build the FCM and make inferences to predict contaminant intrusion in distribution networks.

4.1. Identifying Key Concepts

Figure 3 provides a list of external input concepts for the proposed FCM. Generally, input concepts refer to concepts defined by the user (decision-maker) and cannot be triggered through other concepts. Eleven input concepts are identified in this FCM (identified by arrows in Figure 3). Some intermediate (dummy) concepts have been introduced in order to reduce the dimensionality of the rule bases (shown with yellow boxes).

4.2. Establishing the Structure of FCM

The structure of the proposed FCM for intrusion is shown in Figure 3. The decision actions (such as flushing, cathodic protection, etc.) relevant to intrusion mechanism are not shown in the figures, due to limitation of available space. Each causal relationship in the FCM is represented by a rule set Rm.



Rule-base ($R_{i,j}$):
Antecedent 1 = A_i; $i = 1,\dots, L$; $L = 3$
Antecedent 2 = C_j; $j = 1,\dots, M$; $M = 2$
Consequent = B_k; $k = 1,\dots, N$; $N = 4$
Total number of rules = 3 × 2 = 6

Rule 1 $R_{1,1}$: *If* A_1 *and* C_1 *then* B_1
Rule 2 $R_{1,2}$: *If* A_1 *and* C_2 *then* B_2
Rule 3 $R_{2,1}$: *If* A_2 *and* C_1 *then* B_2
Rule 4 $R_{2,2}$: *If* A_2 *and* C_2 *then* B_3
Rule 5 $R_{3,1}$: *If* A_3 *and* C_1 *then* B_3
Rule 6 $R_{3,2}$: *If* A_3 *and* C_2 *then* B_4

- x_1 has support (membership >0) in A_1 and A_2, and x_2 has support in C_1 and C_2, consequently only the first 4 rules are "fired" (or activated).
- Rule 1: $\mu_{A_1}(x_1) = 0.3$, : $\mu_{C_1}(x_1) = 0.4 \Rightarrow \beta_{1,1} = 0.3 \wedge 0.4 = 0.3 \Rightarrow \mu_{B_1}(y) = 0.3$
- Rule 2: $\mu_{A_1}(x_1) = 0.3$, : $\mu_{C_2}(x_1) = 0.6 \Rightarrow \beta_{1,2} = 0.3 \wedge 0.6 = 0.3 \Rightarrow \mu_{B_2}(y) = 0.3$
- Rule 3: $\mu_{A_2}(x_1) = 0.7$, : $\mu_{C_1}(x_1) = 0.4 \Rightarrow \beta_{2,1} = 0.7 \wedge 0.4 = 0.4 \Rightarrow \mu_{B_2}(y) = 0.4$
- Rule 4: $\mu_{A_2}(x_1) = 0.7$, : $\mu_{C_2}(x_1) = 0.6 \Rightarrow \beta_{2,2} = 0.7 \wedge 0.6 = 0.6 \Rightarrow \mu_{B_3}(y) = 0.6$
- For every subset B_k choose maximum membership, i.e., $\mu_{B_2}(y) = 0.4$
- Define quality ordered weights (q_k) for every subset B_k (assume $q_1 = 0$; $q_2 = 0.3$; $q_3 = 0.7$; $q_4 = 1$)

$$Defuz.(B') = \left(\sum_{k=1}^{N} \mu_{Bk}(y) \bullet q_k \right) = 0.3 \times 0 + 0.4 \times 0.3 + 0.6 \times 0.7 + 0 \times 1$$

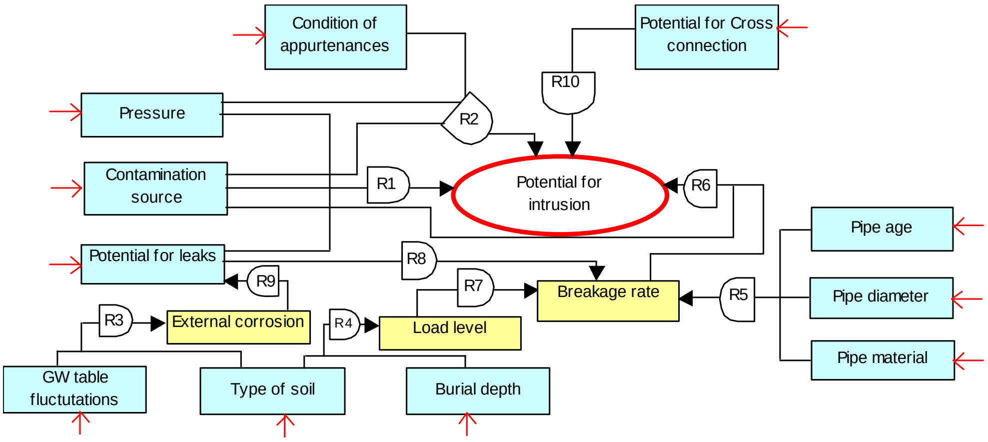
DefuzB' = **0.54**

Figure 2. Making inference using FRBM (modified after [4])

4.3. Defining the Universe of Discourse (U) of Input Concepts

The universe of discourse (*U*) refers to the scale on which each input concept is measured or observed. The universe of discourse defines the intensity of activation signal for each input concept based on their measured or observed values. The table in Figure 3 provides a list of input concepts and their corresponding universe of discourse.

The universe of discourse for input concepts could be a continuous or a discrete set. For example, "pipe age (years)" can be described over a continuous (right open) interval [0, 100[, whereas universe of discourse of "Soil / backfill type" is a discrete set {gravel, sand, silty sand, silt, silty clay, clay}.



Input concepts	Units	*Universe of discourse (U)
Pipe age (C1)	years	[0, 100[
Pipe diameter (C2)	inch	{2, 3, 4, 6, 8, 10, 12, 15, 18}
Pipe material (C3)	type	{CU, CL, DI, PVC, AC}
Condition of appurtenances (C4)	linguistic	{excellent, good, fair, bad, poor} = {0, 0.3, 0.5, 0.7, 1}
Potential for leaks (C5)	linguistic	{negligible, little, medium, high, v. high} = {0, 0.3, 0.5, 0.7, 1}
Potential for X^n (C6)	linguistic	{negligible, little, medium, high, v. high} = {0, 0.3, 0.5, 0.7, 1}
Pressure (C7)	psi	]-20, 20[
Contamination source (C8)	m	]0.5, 5[
Soil / backfill type (C9)	type	{gravel, sand, silty sand, silt, silty clay, clay} = {0, 0.2, 0.4, 0.6, 0.8, 1}
GWT fluctuations (C10)	cycles	{dry/dry, wet/wet, wet/dry} = {0.1, 0.4, 0.8}
Burial depth (C11)	m	]1, 4[

* Discrete set: {*a*, *b*}; Continuous (closed interval) set: [*a*, *b*]; Continuous (left open interval) set:]*a*, *b*]; Continuous (right open interval) set: [*a*, *b*[; Continuous (open interval) set:]*a*, *b*[

Figure 3. Proposed FCM for predicting potential of contaminant intrusion in distribution networks

Universes of discourse of input concepts, which are not quantitative, are converted to numerical values. For example, the discrete set of soil / backfill type is converted to {0, 0.2, 0.4, 0.6, 0.8, 1}, where each number refers to a specific soil type. For input concepts defined over linguistic universes of discourse, each linguistic constant is assigned a numerical score. For example, the universe of discourse of "Condition of appurtenances" is {excellent, good, fair, bad, poor}, transformed into a discrete numerical set of {0, 0.3, 0.5, 0.7, 1}.

4.4. Fuzzifying Input Concepts

After defining the universe of discourse, the observed or measured value of an input concept is mapped over its universe of discourse and membership functions are evaluated with respect to the linguistic constants *low*, *medium*, and *high* (L, M, H). After fuzzification, the input concept can be represented by a three-tuple fuzzy set (μ_L, μ_M, μ_H), corresponding to membership values to constants L, M, and H. This three-tuple fuzzy set is then used to make inferences.

*4.5. Defining the Rule-sets (*Rm*)*

The rule sets Rm are usually MISO type but some SISO type (when there is only one antecedent) exists as well. The inferencing mechanism is the same as described earlier in Figure 2. Ten rule sets (Table 3) are required to completely determine the potential for contaminant intrusion in the model depicted in Figure 3. The details of these rules are not provided in this paper due to space limitation.

4.6. Making Inferences and Estimating Intrusion

After the fuzzification of input concepts, the specific rule sets are used to make inferences at each effect node. Depending on the number of antecedents and type of concepts, appropriate Rm is used to obtain the activation signal at each consequent node, where the ultimate consequent node depicts the potential for contaminant intrusion.

Table 3. Details of rule sets used to determine potential for contaminant intrusion

Rule sets (Rm)	Antecedents	**Consequents	Number of rules ($R_{i,j}$)	Model type
R_1	C7, C8, C6	Potential for intrusion	27	MISO
R_2	C7, C8, C4	Potential for intrusion	27	MISO
R_3	C10, C9	External corrosion	9	MISO
R_4	C9, C11	Load level	9	MISO
R_5	C1, C2, *C3	Breakage rate	9	MISO
R_6	Breakage rate, C8	Potential for intrusion	9	MISO
R_7	Load level	Breakage rate	3	SISO
R_8	C5	Breakage rate	3	SISO
R_9	External corrosion	C5	3	SISO
R_{10}	C6	Potential for intrusion	3	SISO

*pipe material (C3) and age of the pipe (C1) together trigger an activation signal (through a 2-way table not provided in this paper), which is used in a MISO model with pipe diameter (C2) to determine breakage rate
**shaded area represents final output of the FCM model

5. Results and Conclusion

Table 4 provides a summary of results for different scenarios where 8 input concepts were held constant, while three input concepts, namely pressure, contamination source and potential for leakage were varied. The values of input concepts were fed into the

FCM model (Figure 3) and potential for intrusion was determined. The numerical values of potential for intrusion were converted into linguistic scale as described in the footnote of Table 4.

The result shows that potential for intrusion into water mains requires the simultaneous presence of the three elements, pathway, driving force, and contamination source. If one of these elements is missing (or at low activation signal), the potential for intrusion drops significantly. The highest value of potential for intrusion refers to the scenario in which pressure is negative; contamination source is very close to the pathway (i.e., higher potential for leakage).

When interpreting the results, it is important to note that the obtained potential for intrusion denotes ‘possibility’ of intrusion and should not be confused with ‘probability’, of intrusion.

Table 4. Summary of results for different scenarios

Input concepts whose values were held constant		Pressure (psi)	Contamination source (m)	Potential for leakage	Potential for intrusion*
Pipe age (yr.)	20-40	>20	>5m	Negligible	0.20 (VL)
Pipe diameter (inch)	6	>20	3-5m	Negligible	0.21 (VL)
Pipe material	DI	>20	< 0.5m	Negligible	0.22 (V L)
Condition of appurtenances	Excellent	negative	>5m	Negligible	0.23 (VL)
GWT fluctuations	dry / dry	negative	<0.5m	Negligible	0.57 (H)
Type of soil / backfill	Sand	negative	<0.5m	Little	0.80 (VH)
Burial depth (m)	2-3	negative	<0.5m	Medium	0.95 (EH)
Potential for X^n	Negligible	negative	<0.5m	High	1.00 (EH)

*EL extremely low; VL very low; L low; M medium; H high; VH very high; EH extremely high

The suggested approach enables the determination of risk of contaminant intrusion even when available information is incomplete, ambiguous or qualitative in nature. This approach can help utilities establish risk-contours of contaminant intrusion for their distribution network using GIS.

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