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A novel modelling approach to predict risk of water quality failures in deteriorating water mains

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ABSTRACT: The impact of deteriorating pipes on water quality in the distribution network has not been consistently taken into account in decision-making process for pipe renewal. This paper reports on an on-going research project to investigate the effects of aging water mains on water quality in distribution networks and integrating it into the prioritization of pipes renewal decision-making process.

A novel modelling approach was developed to quantify the intricate water quality failures in distribution network. The model can incorporate uncertain, subjective/ linguistic and/ or incomplete data. The proposed model is based on an approach, called fuzzy cognitive map, which is a plausible way to represent and comprehend ill-defined and complex relationships such as those that govern water quality in the distribution network. This paper provides a brief overview of the methodology and the approach developed in this research using a simple hypothetical example.

1 INTRODUCTION - WATER QUALITY DETERIORATION MECHANISMS

Water quality is generally defined by a collection of upper and lower limits on selected performance indicators (Maier 1999). Therefore, a water quality failure (WQF) refers to an exceedance of one or more water quality indicators from specific regulations, or in the absence of regulations, exceedance of guidelines or self-imposed limits driven by customer service needs (Sadiq *et al*. 2004).

Water quality failures that compromise either safety or aesthetics of water in distribution networks, can generally be caused through the following deterioration mechanisms (Kleiner 1998):

a) Intrusion of contaminants;
b) Corrosion byproducts and leaching of chemicals;
c) Regrowth of microorganisms and formation of biofilm;
d) Formation of disinfection byproducts (e.g., THMs) and disinfectant loss;
e) Permeation of organic compounds from the soil, and,
f) Microbial and/or chemical breakthrough due to deficiency in water treatment.

Intrusion of contaminants into a water distribution network can occur through pipes and storage tanks. Open finished water reservoirs are susceptible to microbial contamination from external non-point sources such as feces of infected animals (e.g., beaver, squirrels and rabbits, within the watershed). Intrusion of contaminants into water mains may occur during maintenance and repair events, through broken pipes and gaskets, and through cross connections. Cross connections (a physical connection between a potable and a non-potable water system), without adequate protection can potentially introduce substances that compromise the quality of potable water. Backflow from cross connections may occur when the pressure inside the water main is less than the pressure at the entry point. This can happen when a water main breaks and is de-pressurized for breakage repair, or when peak or fire demands occur, or when a non-potable pressurized system is connected to the potable water network without backflow protection (Kirmeyer *et al*. 2001). Contamination events can also occur as a result of transient pressures in the distribution network, where negative or low pressures cause backflow into distribution mains from surrounding contaminated soils.

The corrosion of metallic pipes and plumbing devices increases the concentration of metal compounds in the water. Different metals go through different corrosion processes, but in general low pH water, high dissolved oxygen, high temperature, and high levels of dissolved solids increase corrosion rates. Heavy metals such as lead and cadmium may also leach into the water from the pipe materials. Secondary metals such as copper (from home plumbing), iron (distribution pipes) and zinc (galvanized pipes) may leach into water and cause taste, odour and colour problems in addition to minor health related risks (Kleiner 1998). Contamination of water by compounds leached from pipe liners (plastic and epoxy lining) has also been observed.

Biofilm is defined as a deposit consisting of microorganisms, microbial products and detritus at the surface of pipes or tanks. Biological regrowth occurs when injured bacteria pass from the treatment plant into the distribution network and subsequently rejuvenate and grow in storage tanks, and water mains. The regrowth of organisms in the distribution network increases chlorine demand, thus reducing the level of free chlorine, which may hinder the network's ability to contend with local occurrences of contamination (US EPA 1999).

Disinfection is the primary method to inactivate pathogens. Chlorine has been highly successful in reducing the incidences of waterborne infections in human beings but other concerns have been raised in the last three decades about the safety of the disinfected water. Harmful disinfection by-products (DBPs) like THMs are formed in the presence of natural organic matter and bromide (from the source) during chlorination (US EPA 1999).

Permeation is a phenomenon in which contaminants migrate through the pipe wall. Three stages are involved in physico-chemical process of permeation: (a) organic chemicals present in the soil partition between the soil and plastic wall, (b) the chemicals defuse through the pipe wall, and (c) the chemicals partition between the pipe wall and the water inside the pipe (Kleiner 1998). In general, the risk of contamination through permeation is relatively small compared to other mechanisms.

Water quality failures attributed to above-listed deterioration mechanisms, with the exception of water treatment deficiency, are closely related to aging water mains in the distribution network. The manifestation of deteriorating (aging) water distribution networks include the increased frequency of leaks and breaks, taste and odour and red water complaints, reduced hydraulic capacity, increased disinfectant demands (due to the presence of corrosion byproducts, biofilms and regrowth). The US EPA (2007) published a series of white papers on these issues, which are available at http://www.epa.gov/safewater/tcr/tcr.html.

This paper is organized into 4 sections. Section 2 explains the basic concepts of the proposed complex modelling approach. Section 3 describes the application of these concepts to the water quality domain. Finally, summary and conclusions are provided in Section 4.

2 MODELLING COMPLEX SYSTEMS

Water distribution networks have typically a limited number of water quality failures each year, making statistically significant generalizations difficult. The rarity of water quality failures belies their seriousness, as each failure indicates the potential for harmful public health effects and increased public mistrust and complaints. In such data-sparse circumstances, expert knowledge and belief can serve as a supplementary and even an alternative source of information.

The modelling of complex dynamic systems requires methods that combine human knowledge and experience as well as expert judgment. 'Soft computing' techniques which includes fuzzy logic, probabilistic & evidential reasoning, and fuzzy measure theory provide an appropriate platform framework to model complex systems with the help of human knowledge and /or available data.

2.1 *Fuzzy cognitive maps*

Fuzzy cognitive maps (FCMs), an extension of cognitive maps, are illustrative causative representations of complex systems (Kosko 1997). FCMs draw a causal representation among all identified factors or concepts of any specific system. A complex system represented by FCM can incorporate human experience, judgment, understanding and knowledge of the system.

FCM consists of nodes, representing factors or concepts that are elements of the system, and weighted arcs (connections and edges), representing causal relationships between nodes. Arcs are graphically illustrated as signed weighted graphs with optional feedback loops. Concepts (nodes) can be inputs, outputs, variables, states, events, actions, goals, and trends of the system. The FCM is a process model, which can use knowledge of expert opinion and belief (qualitative, soft) and/or existing (quantitative, hard) data. Conventional FCMs have three major limitations:

a) Fixed value of causal relationship between two concepts (factors).
b) Lack of a temporal dimension.
c) Inability to handle a process in which the co-occurrence of multiple causes is required to trigger a single 'effect concept'.

Limitations (a) and (c) are addressed in the proposed model, where fuzzy rule-bases and the fuzzy measures are used as arcs to denote/ represent causal relationships among nodes. Brief introduction of these two inference methods is provided below.

2.2 *Fuzzy rule-based models*

Fuzzy rule-based models (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. MISO models can capture co-occurrence of multiple causes, but can also become extremely complex because of dimensionality issues. However, the curse of dimensionality can be managed by introducing intermediate nodes. A fuzzy rule-based model, as described by Zadeh (1973), contains these features:

a) Linguistic variables instead of, or in addition to numerical variables;
b) Relationships between the variables in terms of IF-THEN rules (fuzzy rule-base);
c) An inference mechanism that uses approximate reasoning algorithms to formulate relationships; and,
d) A defuzzification method to obtain crisp output.

2.3 *Fuzzy measures theory*

Complex interactions between factors (i.e., sub- and super-additive) are best introduced by assigning a non-additive set function that permits to assign weights to a subset of factors rather than to an individual factor. It is widely accepted that additivity is not suitable as a required property of set functions in many real situations, due to the lack of additivity in many facets of human reasoning (Ross 2004). Sugeno (1974) proposed to replace the additivity property by a weaker one - *monotonicity* - and called these non-additive (monotonic) measures ‘fuzzy measures’. It is important to note that fuzzy measures are not related to fuzzy sets, which typically are used to express vagueness and human subjectivity.

One possible meaning of a fuzzy measure can be defined as the level of importance or the degree of belief of a single attribute towards the overall evaluation of the system. In this research, a fuzzy measure was used to show the absolute contribution of a single water quality deterioration mechanism towards a given type of water quality failure.

3 PROPOSED APPROACH FOR PREDICTING WATER QUALITY FAILURES

Two-level FCMs were developed in the proposed model. At the lower or modular level, the water quality deterioration mechanisms are estimated using fuzzy rule-based modelling inference mechanisms (Section 2.2). At the higher (or supervisory) level, the water quality failures are estimated using fuzzy measures theory (Section 2.3).

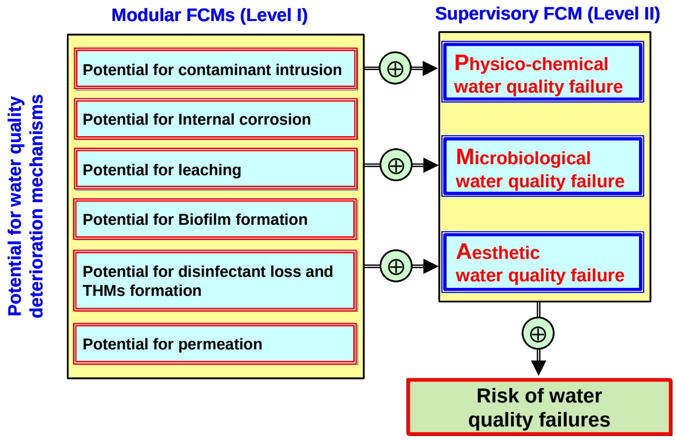


Figure 1. Schematic representation of the proposed model

We have identified many factors/ concepts, which can influence water quality in aging water mains. Out of these factors, approximately fifty factors are selected to the model the water quality in distribution networks. Additional factors may be included in the proposed model, but it does not warrant more reliable outcome. In our selection of concepts we attempt to adhere to the principle of Occam’s razor, “one should not increase, beyond what is necessary, the number of entities required to explain anything”.

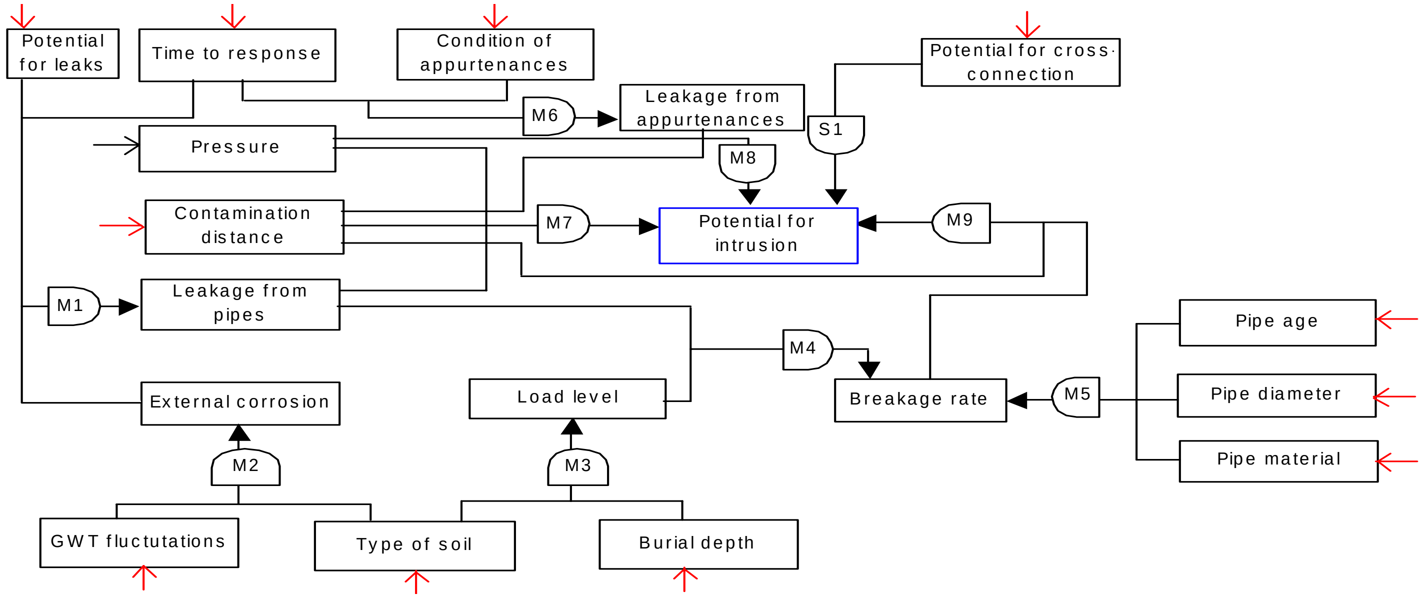


Figure 2. Modular FCM for ‘potential for intrusion (PI)”

Figure 1 above describes the complexity of the proposed FCM. The model was developed using nested FCMs at two levels, as described earlier. At Level I, six modules containing MISO type fuzzy rule-based FCMs were developed to predict potential for various water quality deterioration mechanisms/ pathways including: (a) potential for intrusion (PI), (b) potential for internal corrosion (PC), (c) potential for leaching (PL), (d) potential for biofilm formation (PB), (e) potential for disinfection loss (PD) and potential for THMs formation (PT), and (f) potential for permeation (PP). Each modular FCM comprises a multitude of basic concepts (factors). Figure 2 illustrates an example of the modular FCM for potential for intrusion (PI). The and-gates in Figure 2 represent fuzzy rule-bases to perform causal reasoning as described earlier in Section 2.2.

The inference from each of the six modular FCMs provides an activation signal to Level II (supervisory) FCM, which is used to predict water quality failures. Three different types of water quality failures are identified, including aesthetic (A-WQF), physico-chemical (P-WQF) and microbiological (M-WQF). The overall water quality failure risk is estimated based on these three types of water quality failure.

Many basic concepts are common to more than one of the modular FCMs, e.g., ‘pipe age’, ‘pipe diameter’ etc., which leads to a strong interconnectivity among the concepts. Fuzzy measures were used to infer this interconnectivity and subsequently to account for their non-additivity.

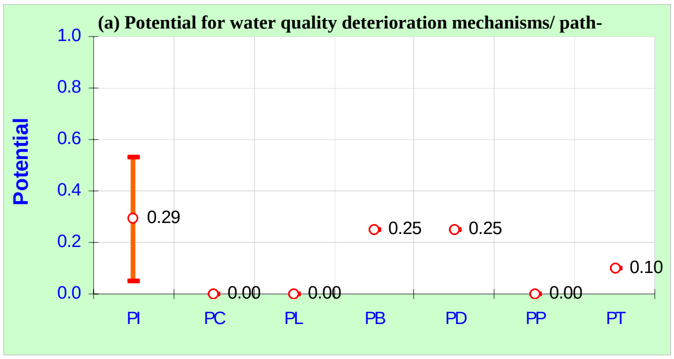
Consider a pipe segment (any pipe length in which input conditions are assumed homogenous) in a water distribution network, for which the potential for water quality failure needs to be determined. Data for the input concepts for this hypothetical pipe length are provided in Table 1. Note that although hypothetical, these data reflect realistic conditions. This data set represents instantaneous or average estimates for the input concepts. Actual magnitudes (e.g., pressure, velocity, or other water quality indicators) may vary over time. Any representative value of these input concepts can be analyzed.

Results of an example using the proposed model are provided in Figure 3, where potentials for the realization of various water quality deterioration mechanisms as well as water quality failures are shown. Three values - minimum, maximum and most likely - are provided for each prediction, using an error bars. The interval [min, max] size is directly proportional to the amount of missing data. For example, the potential for intrusion (PI in Figure 2) has a wide range because the contributing factor “contamination distance” is defined as “No info.” (i.e., missing data) in Table 1.

Table 1. The input values of factors used in the proposed model

Category of factors	Input factors/ concepts	Values
Pipe attributes	Pipe age (years)	20 to 40
	Pipe diameter (inch)	6
	Pipe material	Cast iron (lined)
	Condition of appurtenances	Excellent
	Potential for leaks	Low
	Potential for X^n	Very low
	Pipe lining material	Bituminous
Site specific factors (environs)	Contamination distance (m)	**No info.**
	GWT fluctuations (cycles)	dry / dry
	Type of soil	Silty sand
	Burial depth (m)	3 to 4
	Contamination type	Sewage
Hydraulic / operational factors	Pressure (psi)	> 5
	Time to response	Fast
	Velocity (m/sec)	0.3 to 0.5
	Water age (days)	< 0.3
Water quality indicators	Residual disinfectant type	Chlorine
	Residual disinfectant concentration (mg/L)	0.2 to 0.5
	Water pH	7 to 8.5
	Water temperature (^{O}C)	10 to 15
	Larson ratio	< 0.5
	Dissolved oxygen (mg/L)	2 to 5
	Organic content (mg/L)	< 0.2
	Nutrients	Very low
	Bromide concentration	Very low

The application of the proposed approach has so far been described for a given location and for a single pipe segment in a water distribution network. However, the proposed approach can be extended to full-scale water distribution networks. On a network level application, risk-contours of water quality failures could be established using GIS. These risk-contours may help utilities identify sensitive locations in the water distribution network and prioritize their rehabilitation and control strategies (Sadiq *et al*. 2006). To develop such a risk map (Figure 4), the above analysis is repeated for different pipe segments.


(a) Potential for water quality deterioration mechanisms/ path-

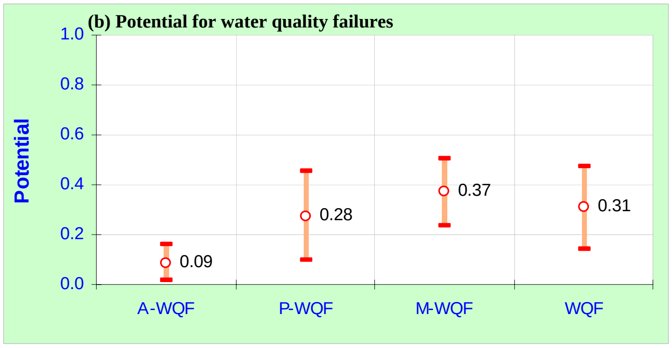

(b) Potential for water quality failures

Figure 3. Results of proposed model predicting potential for water quality deterioration mechanisms/ pathways and water quality failures

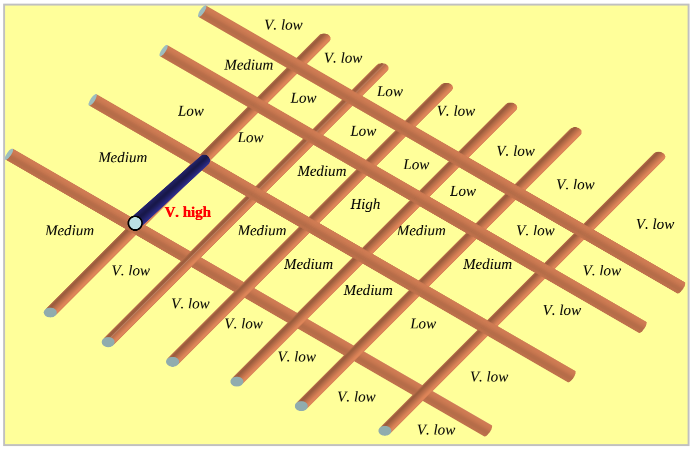


Figure 4. Prioritizing rehabilitation strategies for a distribution network based on water quality failures

4 SUMMARY AND CONCLUSIONS

Numerous factors affect water quality in the distribution networks and the interactions amongst them are complex and often not well understood. Water quality failures in distribution networks are scarce, which make statistically significant generalizations difficult. A predictive model using 2-level, nested fuzzy cognitive maps (FCMs) is proposed to comprehend these ill-defined and complex relationships that govern water quality in the distribution network. At the modular (lower) level, six rule-based FCMs are proposed for various deterioration mechanisms, which contribute to the realization of water quality failure. At the supervisory level, a FCM is proposed which employs fuzzy measures to interpret activation signals received from the modular FCMs to predict water quality failure risk in distribution networks.

The proposed method will help quantify the risk of water quality failures in a given pipe. The method can be extended to an entire network by way of creating iso- risk-contours. The risk-contours may help utilities identify sensitive locations in the water distribution networks using GIS and prioritize decision strategies.

5 ACKNOWLEDGMENTS

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