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Fuzzy risk-based decision-making approach for selection of drinking water disinfectants

Shakhawat Chowdhury, Pascale Champagne and Tahir Husain

ABSTRACT

The potential effects of disinfection by-products (DBP) on human health have become a serious concern over the last three decades. In addition to the chronic cancer risk, several acute effects such as cardiac anomalies, stillbirths, miscarriages, low birth weights and pre-term deliveries have also been reported as a result of exposure to the DBP. Although several disinfectants including chlorine, ozone, ultraviolet ray (UV) radiation, chloramine and chlorine dioxide are available to supply safe drinking water, comparative evaluations of these disinfectants and their application approaches for a particular source of water is rare. This may be due to the variability associated with predicting DBP formation, health effects from DBP exposure, cost and disinfection performance of various disinfectants used in public water supply systems; and/or the knowledge gap in the assessment and comparison of risks associated with specific disinfection strategies. In this study, a framework for comparative evaluation of disinfectants and their application approaches has been developed through incorporation of human health risk from DBP exposure, cost of disinfection process, technical feasibility and disinfection performance. A fuzzy synthetic evaluation technique has been incorporated where fuzzy triangular membership functions were developed to capture uncertainties of the basic attributes. This paper compared three disinfection approaches: chlorination, chloramination and granular activated carbon with post chlorination through a multi-stage hierarchy risk model in which the analytical hierarchy process has been used to determine the relative importance of various attributes at different hierarchy levels. Then the best disinfection approach has been outlined. This evaluation was found to be sensitive to the assignment of relative importance.

Key words | analytic hierarchy process and uncertainty, disinfection by–products (DBP), fuzzy synthetic evaluation, human health risk

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INTRODUCTION

The introduction of chlorination for drinking water disinfection has virtually eliminated most waterborne diseases from drinking water ingestion (USCDC 1997). Despite the enormous success in supplying safe drinking water to communities through the use of disinfectants, disinfection by-products (DBP) have become a serious health concern since their discovery in drinking water (Rook 1974). Approximately 14–16% of bladder cancers in Ontario (Canada) can be attributed to drinking waters containing relatively high levels of chlorinated by-products (King & Marrett 1996; National Cancer Institute 1998; Wigle 1998). Increased risks of colon and rectal cancers, as well as adverse reproductive and developmental effects including increased spontaneous abortion rates, stillbirths, cardiac anomalies, pre-term deliveries low birth weights and fetal anomalies are also attributable to DBP (Mills *et al.* 1998; Waller *et al.* 1998; King *et al.* 2000; Richardson *et al.* 2002; Villanueva *et al.* 2004). Although potentially carcinogenic unregulated DBP have recently been reported (Richardson

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2005), the most investigated DBP include trihalomethanes (THM); haloacetic acids (HAA); haloacetonitriles (HAN) and haloketones (HK). Each of these DBP groups is composed of many compounds (Table 1). Some of the DBP in Table 1 have carcinogenic effects on animal and probable and possible human carcinogens (Bull *et al.* 1985, 1990; Smith *et al.* 1988; Pereira 1996; Mills *et al.* 1998; King *et al.* 2000). Some of the data in Table 1 is missing, which reveals the fact that studies on human health effects from a significant fraction of regulated and unregulated DBP is yet to be performed (King & Marrett 1996; Richardson 2005; USEPA 2005). Conversely, the *International Programme on Chemical Safety* (IPCS) reported that health risks associated with DBP in drinking water are extremely small in comparison to the health risks associated with inadequate disinfection (IPCS 2000). In Walkerton (Ontario, Canada), seven people died and more than 2,300 became ill after the *E. Coli* contamination of the community's municipal water supply system in the year 2000 (MOE 2002). In April 1993, more than 400,000 people were affected by a drinking water outbreak in Milwaukee (USA), which resulted in the death of approximately 100 people (MacKenzie *et al.*

Table 1 | Components of DBPs in drinking water and their effects

Main Group	Compounds	Effects to animal	Effects to Human	Source
Trihalomethanes (THMs)	Chloroform	Liver Tumours	Probable human carcinogen (B-2)	NCI (1976); IRIS (2006)
	Bromodichloromethane	Kidney tumour	Probable human carcinogen (B-2)	NTP (1987); IRIS (2006)
	Bromoform	Colon tumours	Probable human carcinogen (B-2)	NTP (1989); IRIS (2006)
	Dibromochloromethane	Liver tumours	Possible human carcinogen (C)	NTP (1984); IRIS (2006)
Haloacetic Acids (HAAs)	Bromochloroacetic Acid	Liver tumours		Bull *et al.* (1990)
	Bromodichloroacetic Acid	Liver tumours		Bull *et al.* (1990)
	Chlorodibromoacetic Acid			
	Dibromoacetic Acid	Liver tumours		Bull *et al.* (1990)
	Dichloroacetic Acid	Liver tumours	Probable human carcinogen (B-2)	Pereira (1996); IRIS (2006)
	Monobromoacetic Acid			
	Monochloroacetic Acid			
	Tribromoacetic Acid			
	Trichloroacetic Acid	Liver tumours	Possible human carcinogen (C)	Pereira (1996); IRIS (2006)
Haloacetonitriles (HANs)	Bromochloroacetonitrile	Embryo death		Smith *et al.* (1988)
	Dibromoacetonitrile	Skin tumours		Bull *et al.* (1985)
	Dichloroacetonitrile	Embryo death		Smith *et al.* (1988)
	Trichloroacetonitrile	Embryo death		Smith *et al.* (1988)
Haloketones (HKs)	1,1 - dichloropropanone			
	1,1,1-trichloropropanone			

1994). The World Health Organization (WHO) reported that approximately 3.4 million people, mostly children, die every year from water-related diseases in the developing countries (WHO 2002); consequently, efficient disinfection should never be compromised (Health Canada 1995, 1996; IPCS 2000; USEPA 2006).

Several steps are generally followed to treat and disinfect surface water for drinking purposes. The typical practice is to remove suspended materials, weeds, etc. and control aquatic invertebrate (such as zebra mussels) at the inlet through screening (Figure 1a). Some water treatment plants use pre-chlorination/chloramination or potassium permanganate in addition to screening at the inlet (for example, Kingston Central Water Treatment Plant, Ontario) to control aquatic invertebrate and remove odor and color (widely used in Ontario; MOE 2004). Then the water enters to the plant where coagulation/flocculation is done through addition of coagulant (typically, alum), mixing and settling. This process reduces DBP precursors, turbidity and pathogens (Dempsey *et al.* 1984; Reckow & Singer 1984; Edzwald 1993; Shorney *et al.* 1999). The water is then filtered to a contact chamber and disinfectant (typically chlorine or chloramine) is added and given the required contact time to provide disinfection and maintain required free chlorine residual throughout the distribution systems (Utilities Kingston 2006). The pretreatment before addition of chlorine/chloramine (e.g., screening, pre-chlorination/chloramination (optional), coagulation, flocculation, settling and filtration) is the most common activity that the water supply systems perform. However, pretreatment cannot completely remove the precursors of DBP as well as pathogens (Clark *et al.* 1998; Chang *et al.* 2001). Numerous water treatment plants (For example, Kingston Central Water Treatment Plant, Ontario) use granular activated carbon (GAC) in addition to the conventional filtration before water enters the contact chamber (Figure 1b) and then disinfectant is applied (Utilities Kingston 2006). Use of GAC effectively reduces NOM and other chemicals through adsorption and catalytic degradation; consequently, formation of THM is expected to be less (Chang *et al.* 2001). The water sources with higher levels of contaminants often use GAC in addition to the conventional filtration (such as, Miller Treatment Plant on the Ohio River, where additional filtration/adsorption is performed by GAC to remove industrial and spilled chemicals). However, not all the systems use GAC because of its higher cost and maintenance (Reiff 1995; DOE 2006). The GAC reduces NOM; thus a smaller amount of disinfectant is generally required. Some water treatment plants also perform fluoridation to ensure dental health.

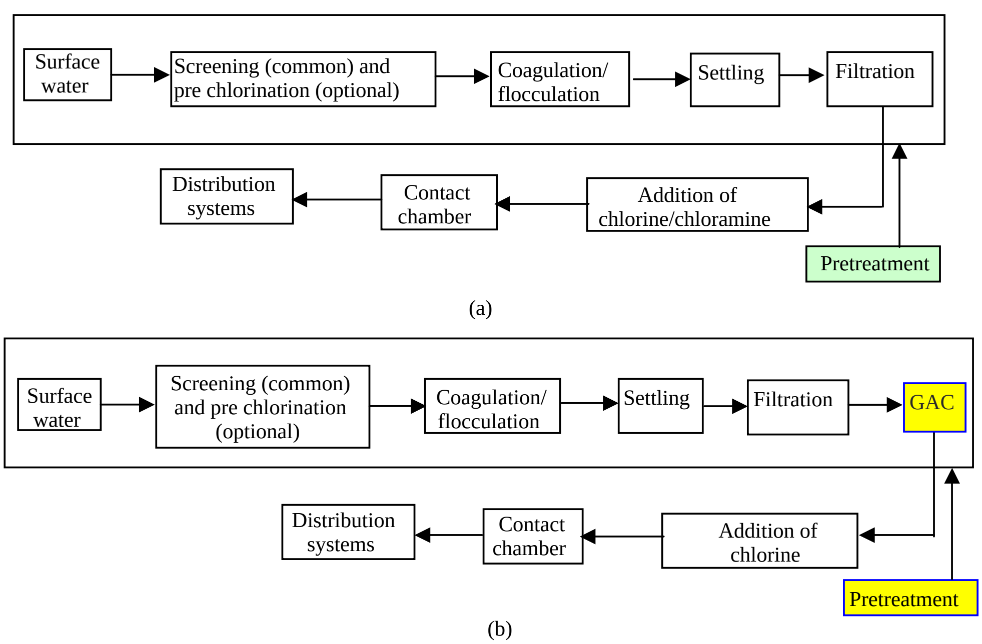

Figure 1 | Typical configuration of water treatment plant; (a). Conventional water treatment plant; (b). Addition of granular activated carbon (GAC).

To date, research has addressed most of the issues associated with water supplies. Edzwald *et al.* (1985) suggested the use of UV absorbance capacity at 254 nm to characterize DBP formation precursors. Some papers have discussed the performance of enhanced coagulation in reducing DBP precursors, pathogens and turbidity (Dempsey *et al.* 1984; Reckow & Singer 1984; Edzwald 1993). Clark *et al.* (1994, 1998) assessed the performance of various disinfectants in terms of DBP formation and costs. However, this study did not include the disinfection efficiencies of various disinfectants nor the human health risk from DBP exposure. Lykins *et al.* (1994) presented a comparative performance study for four types of disinfectants (ozone, chlorine dioxide, chlorine and chloramine); however, their study was only limited to the performance of pathogen removal. Reiff (1995) presented a comparative evaluation of the chemical and microbial risks associated with disinfection, but no specific information on disinfection performance or human health risk was noted in the study. Chowdhury & Husain (2005) presented human health risks from trihalomethanes (THM); however, this study did not consider other aspects such as cost, technical feasibility and disinfection performance of the disinfectants. Chowdhury & Husain (2006) presented an entropy based fuzzy evaluation of disinfection approaches, in which the approach of integrated importance through combining subjective and objective importance has been incorporated.

In decision-making for the selection of disinfection approaches, many factors including DBP formation and human health risks from DBP exposure, availability of drinking water treatment options, disinfection performance and cost must be considered. Human health risk is often one of the most significant factors involved in decision-making (Lee 1992; Connor *et al.* 1995; USEPA 1998). Risk assessment models and risk-based management strategies are widely used in the field of environmental management (Lee 1992; Khadam & Kaluarachchi 2003; USEPA 2006). Some of the risk assessment models have parameters that are often poorly characterized, correlated or simplified; leading to inherent model uncertainties (Ferson 1996; Guyonnet *et al.* 1999). Moreover, in human health risk assessment, a major portion of available information on DBP ingestion rates, exposure durations, human body weights and dose-response is partially known or vaguely characterized through a series of simplifications (USEPA 1998). To capture these uncertainties, a number of techniques have been employed (Khadam & Kaluarachchi 2003) in risk assessment studies. The sampling-based technique, more specifically the *Monte Carlo* (*MC*) simulation is widely used for such purposes (USEPA 1996). However, to be applied successfully, this method requires (i) information on statistical dependencies among the variables; (ii) sufficient data in comparatively precise form to generate statistical distributions; and (iii) information on the model structure (Ferson 1996; Guyonnet *et al.* 1999). Moreover, in *MC* simulations, lower probability parameter values generally have fewer chances of being randomly selected; therefore a portion of the possible data could be ignored (Guyonnet *et al.* 1999). From a regulatory aspect, limitations on human health cancer risks typically vary within 10^{-4} to 10^{-6} (USEPA 1991), which indicates a single occurrence in 10,000 to 10,00,000. To obtain a representative number of occurrences of risk exceedance, the simple *MC* simulation often needs millions of iterations (Ferson 1996). More fundamentally, probabilistic models use equiprobability in dealing with incertitude and hence cannot distinguish between uniform risk and a simple lack of knowledge. In most practical risk assessments, some uncertainty is epistemic rather than aleatory, that is, the uncertainty is due to incertitude rather than data variability; thus confounding effects may be resulted from probabilistic models (Dubois & Prade 1992; Neumaier 2004).

The use of fuzzy sets in the analysis of imprecise data and its application to environmental problems has been demonstrated with an acceptable degree of confidence (Chen & Hwang 1992; Klir &Yuan 1995; Zimmermann 2001). Fuzzy risk-cost trade-off approaches have been employed in diverse fields including nitrate-contaminated groundwater supplies (Lee 1992), evaluating the performance of tanks in battle (Cheng & Lin 2002), risk-based indexing system (Sadiq & Rodriguez 2004) and software development (Lee 1996). The fuzzy synthetic evaluation technique has recently been applied in drilling waste management from offshore oil and gas industries (Sadiq *et al.* 2004) and risk-based indexing system (Sadiq & Rodriguez 2004). Cheng & Lin (2002) used the maximum operator to determine classification of fuzzy subsets from a final fuzzy set.

In this paper, the overall status of three water treatment systems is presented through human health risk from DBP exposure, cost of disinfectants, technical feasibility and disinfection performance. The fuzzy synthetic evaluation (FSE) technique is incorporated where fuzzy triangular membership functions characterize uncertainties of the basic attributes. Finally, an example in the application of FSE to select the best disinfection approach is illustrated.

FORMATION OF DBP

The naturally occurring organic matter (NOM) in surface waters reacts with disinfecting agents such as chlorine, chloramine, ozone, etc. in the treatment plant and distribution systems to produce DBP. The formation of trihalomethanes has been found to be the highest, followed by haloacetic acids, haloacetonitriles and haloketones in drinking water (Singer *et al.* 1981; Shorney *et al.* 1999; Kim *et al.* 2002; Kolla 2004; MOE 2004). The presence of bromide ions in chlorinated water results in the increased formation of brominated species of DBP (Symons *et al.* 1993), which are more carcinogenic to human health (Richardson 2005; IRIS 2006) and, consequently, a reduction in the formation of chlorinated species (Nokes *et al.* 1999; Barrett *et al.* 2000). Trihalomethanes formation typically increases with increasing pH (Oliver & Lawrence 1979; Kim *et al.* 2002; Latifoglu 2003), while haloacetic acids and haloacetonitriles formation generally decrease with increasing pH (Singer 1994; Kolla 2004). Stevens *et al.* (1976) and Kolla (2004) reported higher DBP formation at higher temperatures. An increase in NOM in water is represented by a higher UV absorbance capacity, which is employed as a surrogate measure of NOM in water, and increased DBP formation (Edzwald *et al.* 1985; Garcia-Villanova *et al.* 1997; Li *et al.* 1998; Sung *et al.* 2000; Clark *et al.* 2001). Although, most of the DBP are formed rapidly within a few hours of reaction between organic and chlorinated species, the contact period in the treatment plant and distribution systems may add significant amount of DBP in drinking water (Kim *et al.* 2002; USEPA 2006). Thorough reviews on DBP formation in drinking water have been presented in Chowdhury & Champagne (2006). The factor wise effects can be summarized as:

(i) Increase in pH within the normal operation range (6.5–8.5) increases the formation of DBP (Stevens *et al.* 1976).
(ii) Increase in reaction time increases THM formation (Gang *et al.* 2002). However, some of the initially formed DBP such as haloacetonitriles and haloketones decay with time as a result of hydrolysis and reactions with residual chlorine (Nikolaou *et al.* 1999).
(iii) At higher temperatures, reaction rates generally increase, yielding a higher rate of THM formation (Stevens *et al.* 1976; Engerholm & Amy 1983).
(iv) Bromide ions can be an important factor for THM formation in coastal areas (Symons *et al.* 1993; Black *et al.* 1996), while brominated species generally present a greater human health concern than chlorinated DBP (IRIS 2006; Richardson 2005).
(v) The NOM has been found to be important in characterizing THM formation (Edzwald *et al.* 1985; Sung *et al.* 2000; Clark *et al.* 2001), where a good correlation between NOM and THM has been reported in the literature (Pelizetti *et al.* 1994; White *et al.* 2003).
(vi) The chlorine demand is positively correlated with THM formation (Rook 1974; Peters *et al.* 1980; Clark *et al.* 1998, 2001; El-Shahat *et al.* 2001).
(vii) The TOC and DOC have good correlations with THM formation (Edzwald *et al.* 1985; Muller 1998; Westerhoff *et al.* 2000; Chang *et al.* 2001; Kolla 2004).

DISINFECTANTS

The widely used disinfection approaches include application of chlorine/chlorine, chlorine/chloramine, granular activated carbon with post chlorination, ozone/chlorine, ozone/chloramine, chlorine dioxide/chlorine, chlorine dioxide/chloramine, UV radiation/chloramine and UV radiation/chlorine. Ozonation and UV radiation are extremely costly as primary disinfectants (4–10 times more than chlorination) and do not provide residual protection in the distribution systems (Clark *et al.* 1994; Lykins *et al.* 1994; USEPA 2006). Hence there is a need for additional chlorine or chloramine for residual protection (MOE 2004; USEPA 2006). In most drinking water supply systems where water requirement is comparatively small ($<=$ 10,000 population), the cost of ozonation and UV radiation may become several times higher than the conventional chlorination (Clark *et al.* 1994; Reiff 1995; USEPA 2006). Moreover, waters containing bromide ion may form bromate with ozone, which is potentially dangerous (regulatory limit 10 ppb) to human health (WHO 2000; USEPA 2006). Increased formation of dihaloaldehydes were also reported at a plant using chloramines and ozone (Richardson 2005).

More than 80% of water treatment plants in the USA and Ontario, Canada use chlorine disinfection in drinking water supply systems (AWWA 2000; MOE 2004). Chlorine is an oxidant and has been proven effective against waterborne microbes. It can also be employed to provide residual protection to inhibit microbial growth in the distribution systems. To date, it is the least expensive disinfectant available, where disinfection costs range from US$ 0.2 to $0.8/person/year (Clark *et al.* 1994; Reiff 1995). The chlorination approaches (liquid, sodium hypo chloride, gas injection) are widely available and easy to maintain (Health Canada 1995; Reiff 1995; AWWA 2000). However, the potential by-products formed as a result of chlorination are of concern to human health (Mills *et al.* 1998; King *et al.* 2000; Villanueva *et al.* 2004).

Chloramine is a weaker disinfectant, which generally needs a considerably higher contact period and dosage to achieve the same level of disinfection as chlorination (Lykins *et al.* 1994; Health Canada 1995; MOE 2004). It is stable and provides a long-term after effect where the growth of microbes is inhibited in the distribution systems. Chloramine produces very low concentrations of halogenated DBP. It has been found to be harmful to patients on kidney dialysis and may form nitrogenous DBP like *N*-Nitrosodimethylamine (Mitch & Sedlak 2002). Formation of some unregulated DBP as a result of chloramine usage has been recently reported (Richardson 2005). These new DBP have associated risks, which are several orders of magnitude higher, in terms of carcinogenic effects on human health, than other well-known DBP (Richardson 2005). Chloramination typically involves the shipment and handling of ammonia compounds and chlorinating chemicals, as well as requiring considerable storage to allow a sufficient contact period (USEPA 2006). Generally, chlorine requires 15–20 minutes to complete germicidal activities in the treatment plants, while in the case of chloramine, the time requirement may exceed one hour (Metcalf & Eddy 2001; USEPA 2005). Although chloramine requires additional reaction time, for smaller communities with sufficient storage capability, chloramine can fairly be used (WHO 1993, 2002; Lykins *et al.* 1994; MOE 2004). Chloramine is also used as a secondary disinfectant (Health Canada 1995; MOE 2004).

Chlorine dioxide is effective in removing/inactivating microbial contaminants (Lykins *et al.* 1994). Chlorine dioxide is volatile and unable to provide residual protection (Lykins *et al.* 1994). However, with an efficient secondary residual disinfectant, chlorine dioxide disinfection can be provided (Health Canada 1995). In Canada and the USA, the use of chlorine dioxide is available with chlorine/chloramine as secondary disinfectant (Health Canada 1995; USEPA 2006). The cost for chlorine dioxide is considerably higher than chlorine (Clark *et al.* 1994) as chlorine dioxide has to be generated on-site leading to the need for transport and storage of chemicals on-site and a facility designated to the required chemical mixing, which can lead to high operational costs. These additional costs and ineffectiveness in the distribution systems inhibit the use of chlorine dioxide. Additionally, use of chlorine dioxide may form chlorite, which is also potentially dangerous to human health (regulatory limit: 1.0 mg/L). Richardson (2005) reported increased formation of MX analogs, which are higher order carcinogens to humans, in the treatment plant using chlorine dioxide/chlorine.

Granular activated carbon (GAC) with post chlorination is another disinfection approach, in which GAC is used, before performing chlorination in the contact chamber, to reduce NOM and other chemicals and has been successfully employed in many water supply systems (MOE 2004). However, the use of GAC can increase operational costs by up to 30–50% of that of conventional chlorination (Clark *et al.* 1994, 1998; Lykins & Clark 1994; Reiff 1995; USEPA 2006). Partial removal of precursors can be achieved using GAC; which subsequently leads to a reduction in DBP formation (Clark *et al.* 1998; Chang *et al.* 2001) compared to chlorination without GAC. However, the efficiency of GAC reduces with time. Lykins & Clark (1994) presented the efficiency reduction of GAC with time, where the initial precursor removal efficiency was 83–98%, which reduces to 35–63% in 90 days. The use of GAC with post chlorination improves finished water quality and generally provides better human health protection by reducing human health risk.

Following the cost, risk and operational feasibility, three approaches: chlorination, chloramination and granular activated carbon with post chlorination have been selected to present the framework. However, the other options can also be evaluated through a similar approach.

FUZZY SET THEORY

Fuzzy set theory provides a language for imprecise, qualitative and vague information converting it into numerical reasoning (Zimmermann 2001). It is a method, which enables the incorporation and manipulation of imprecise data where information is limited, qualitative or sparse, which provides an advantage over other uncertainty characterization approaches. Fuzzy set theory incorporates possible parameter values through membership functions (Guyonnet *et al.* 1999). A fuzzy set establishes the relationship between uncertain data and the membership function μ, which ranges from 0 to 1. The membership function $\mu_a(x)$, is defined as the fuzzy subset a in the universe of discourse x. For example, fuzzy triangular membership function (TFNs) for Figure 2 can be constructed as:

$$\mu_a(x) = \begin{cases} (x-a)/(b-a), & a \le x \le b \\ (x-c)/(b-c), & b \le x \le c \\ 0, & \text{otherwise} \end{cases} \quad (1)$$

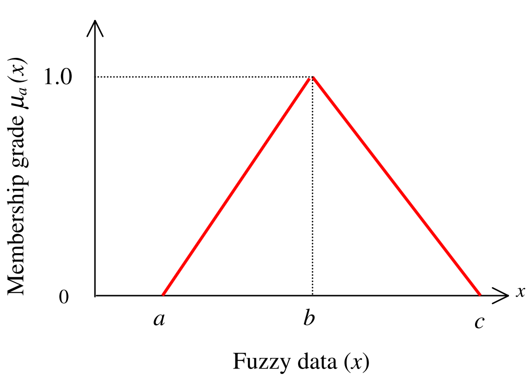

Figure 2 | Construction of membership function.

The TFNs are defined by (a, b, c), where a and c represent the minimum and maximum values and b represents the most likely value (Figure 2). For the most likely value, the membership grade is assigned as unity. In traditional set theory, an element is identified as being a member of a set (say, ***A***) or not. If the element is in set ***A***, the membership grade is unity; otherwise it is zero. A fuzzy set is an extension of the traditional set theory in which the element possesses a certain degree of membership μ (0 to 1) in set ***A***. Triangular fuzzy numbers and trapezoidal fuzzy numbers are mostly utilized to represent the linguistic scales (high, medium, low) employed by managers, professionals and stakeholders (Lee 1996). Fuzzy multi-criteria decision-making (MCDM) is a step-by-step process. The sequences of fuzzy evaluation are described as follows:

1. **Definition of basic attributes and hierarchical framework** First, the attributes necessary for decision-making are identified and the generalized attributes are broken into their basic attributes (Figure 3). In the case study presented, the system index (a) is divided into four general attributes as human health risk from DBP (a_1); cost (a_2); technical feasibility (a_3) and disinfection performance (a_4) as shown in Figure 3. At the next level, the attribute disinfection performance (a_4) has been separated into two attributes: microbial (a_{41}) and aesthetic (a_{41}) risk reduction and these are subsequently divided into their basic attributes as shown in Figure 3. The basic attributes are typically in different units (risk: unit less; cost: $/person/year) and can include data in the form of crisp, fuzzy or in linguistic terms. These will next be transformed into a homogeneous scale using fuzzification technique.
2. **Fuzzification of basic attributes** The basic attributes are generally expressed in 5 to 9 scales (Saaty 1988) to incorporate the natural variability expressed by expert judgments. In this case study, six linguistic scales: worst, bad, poor, fair, good and best have been selected for simplicity (Lee 1996). Once the fuzzy data is defined, the basic attributes are expressed with membership grades in the six pre-defined scales (μ_1, μ_2, μ_3, μ_4, μ_5, μ_6) representing worst, bad, poor, fair, good and best, respectively. For example in Figure 4, an element ***P*** is fuzzified as **(0.5, 0.62, 0.7)**, for which the fuzzy data

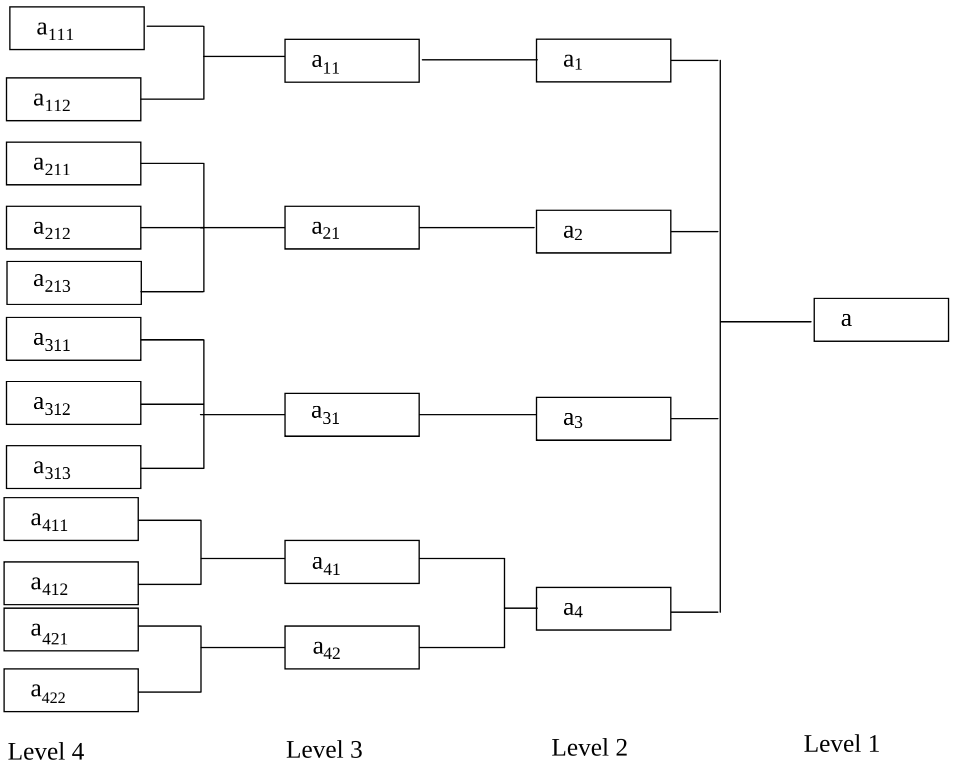

Figure 3 | Framework for different attributes and fuzzy evaluation.

indicates a triangular fuzzy number in the range of 0.5–0.7, with a most likely value of 0.62. If the variable ***P*** intersects any scale more than once, the maximum operator is used to define the fuzzy subsets (Yager & Filev 1994). In the case of variable ***P*,** a membership grade for μ_1(worst) = 0, μ_2(bad) = 0, μ_3(poor) = 0.33, μ_4(fair) = max (0.97, 0.88), μ_5(good) = 0.36 and μ_6(best) = 0 would be determined. As such, the fuzzy sets would become (0, 0, 0.33, 0.97, 0.36, 0). If ***P*** were in crisp number, the approach would be similar. Figures 5 to 9 represent fuzzy scales for other attributes: cancer risk (Figure 5), non-cancer risk (Figure 6), cost (Figure 7), technical feasibility (Figure 8), and risk reduction (Figure 9). The fuzzy data are mapped on corresponding scales to obtain fuzzified data and shown in Table 5.

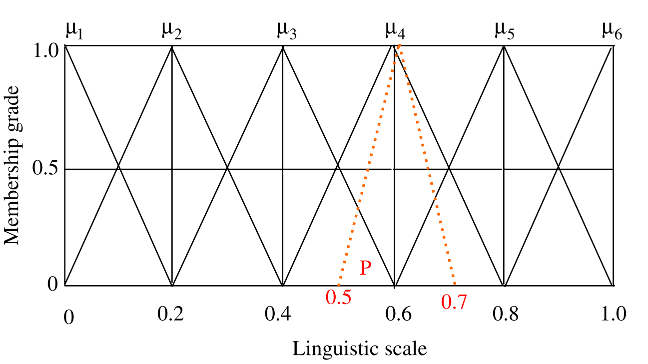

Figure 4 | Defining fuzzy membership function.

3. **Definition of relative weights** Fuzzy evaluation requires that the relative importance of different attributes at each level be determined. The analytic hierarchy process (*AHP*) is a popular method, which was introduced by Saaty (1988) to define the relative importance of each attribute. The fundamental scales of importance to

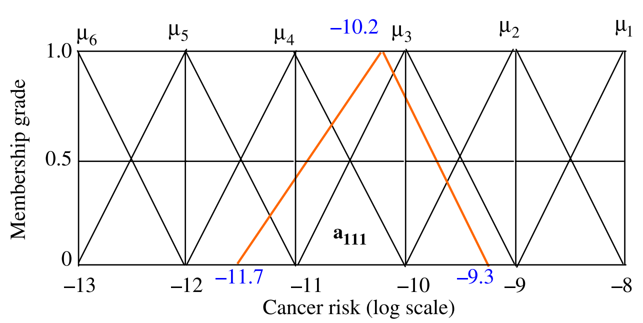

Figure 5 | Membership function for cancer risk (log-scale).

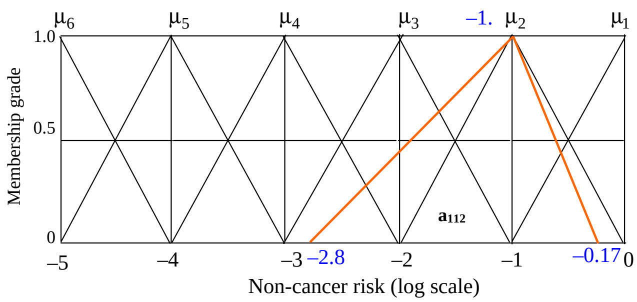

Figure 6 | Membership function for non-cancer risk (log-scale).

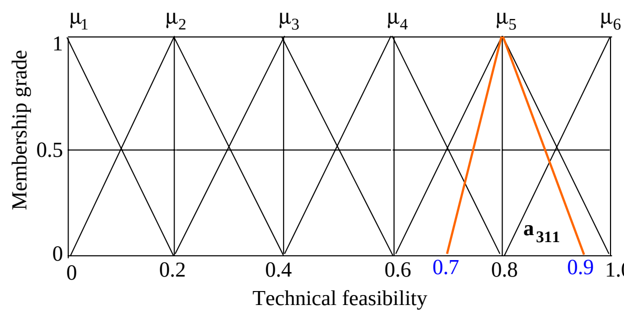

Figure 8 | Membership function for technical feasibility.

develop priority matrices can be found in Saaty (1988). These were employed to construct the priority matrix for this case study. The priorities are then normalized and the priority matrix is formed in such a way that the sum of the relative importance for all attributes in a group equals to unity (Saaty 1988; Chowdhury & Husain 2006), as:

$$W = (w_1, w_2, \ldots\ldots\ldots w_n) \quad \text{where} \quad \sum_{k=1}^{n} w_k = 1$$

For examples: In level 3, the attribute cost (a_{21}) is composed of three basic attributes: technology cost (a_{211}), operational cost (a_{212}) and maintenance cost (a_{213}) (Figure 3). From expert judgments (Sadiq *et al.* 2004; DOE 2005; Chowdhury & Husain 2006), it is assumed that attribute of technology cost (a_{211}) is 2 times more important than operational cost (a_{212}) and 2.5 times more important than maintenance cost (a_{213}). However the relative importance may be a range other than a crisp number. In such cases, solution may require max-min paired elimination technique (Xu & Zhai 1992). For simplicity, crisp numbers were used for relative importance. In the priority matrix, each element of the lower triangle in the matrix is reciprocal to the upper triangle (Saaty 1988). The matrix is thus formed as:

$$W_{21} = \begin{array}{cccc} & a_{211} & a_{212} & a_{213} \\ a_{211} & 1 & 2 & 2.5 \\ a_{212} & 0.5 & 1 & 1.25 \\ a_{213} & 0.4 & 0.8 & 1 \end{array} \qquad (2)$$

The matrix W can be formed by taking the row-wise geometric mean of the elements and normalizing to unity (Saaty 1988; Chowdhury & Husain 2006) as:

$$W_{21} = \begin{bmatrix} 0.526 \\ 0.263 \\ 0.211 \end{bmatrix} \qquad (3)$$

Priority matrices for the other attributes can be developed in a similar fashion and are shown in Table 6.

4. **Generation of more generalized attributes by aggregation** Once the relative importance and fuzzy sets for the basic attributes have been defined, these are then grouped according to the hierarchy framework as illustrated in

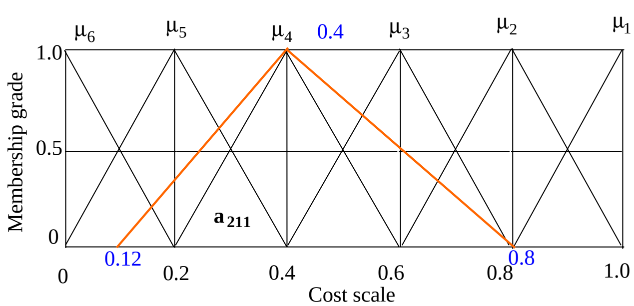

Figure 7 | Membership function for cost ($ per person per year).

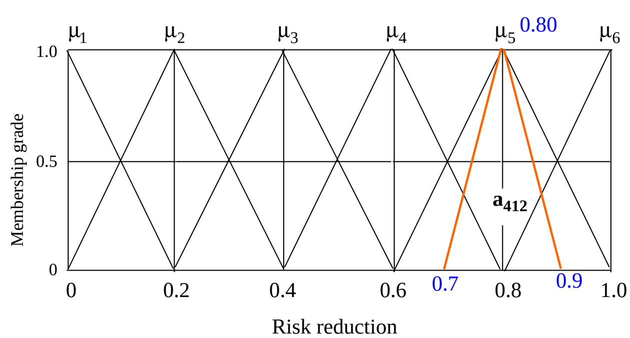

Figure 9 | Membership function for risk reduction.

Figure 3. For instance, the fuzzy subsets for a_{21} form an assessment matrix as shown in Table 5: 1st column

$$a_{21} = \begin{bmatrix} a_{211} \\ a_{212} \\ a_{213} \end{bmatrix} = \begin{bmatrix} \mu_1^{211}, & \mu_2^{211}, & \mu_3^{211}, & \mu_4^{211}, & \mu_5^{211}, & \mu_6^{211} \\ \mu_1^{212}, & \mu_2^{212}, & \mu_3^{212}, & \mu_4^{212}, & \mu_5^{212}, & \mu_6^{212} \\ \mu_1^{213}, & \mu_2^{213}, & \mu_3^{213}, & \mu_4^{213}, & \mu_5^{213}, & \mu_6^{213} \end{bmatrix} = \begin{bmatrix} 0 & 3.7 & 0.7 & 1.0 & 0.61 & 0.21 \\ 0 & 0 & 0 & 0 & 0.67 & 0.48 \\ 0 & 0 & 0 & 0 & 0.54 & 0.66 \end{bmatrix}$$

The priority vectors for the three attributes are (Equation 3)

$$W_{21}^T = \begin{bmatrix} W_{211} & W_{212} & W_{213} \end{bmatrix} = \begin{bmatrix} 0.526 & 0.263 & 0.211 \end{bmatrix}$$

The evaluation matrix A_{21} for a_{21} is obtained using the priority vector W_{21}^T

$$A_{21} = W_{21}^T \times a_{21} = \begin{bmatrix} 0 & 0.195 & 0.368 & 0.526 & 0.611 & 0.376 \end{bmatrix} \quad (4)$$

Similarly, the evaluation matrices for other attributes are developed until a complete final fuzzy set is generated.

5. **Defuzzifying the final data sets and ranking the alternatives.** Decision-making is generally performed using crisp values. In fuzzy set theory, these crisp values are obtained through defuzzification, which can be performed using a number of available methods (Chen & Hwang 1992). Cheng & Lin (2002) used a maximum operator to determine the classification of fuzzy subsets from a final fuzzy set. Different weights assigned to the membership grades are generally employed for fuzzy synthetic evaluations (Sadiq *et al.* 2004; Lu *et al.* 1999). The following equation represents the highest value of membership, which determines the classification of fuzzy sets.

$$U_a = \max(\mu_1, \mu_2, \mu_3, \mu_4, \mu_5, \mu_6) \quad (5)$$

where, U_a = utility function
An optimistic attitude focuses more on the more positive memberships of a qualitative scale; where higher weights are assigned to the more positive outcomes of qualitative scales (Cheng & Lin 2002). A similar optimistic attitude is employed in this case study and the utility function can be derived as:

$$U_a = 0.5\mu_1 + \mu_2 + 2\mu_3 + 4\mu_4 + 6\mu_5 + 10\mu_6 \quad (6)$$

It should be noted that this 'optimistic attitude' issue is quite subjective to the selection of the decision-makers and that the values of the coefficients are arbitrary. These can be refined through inclusion of expert judgments in the respective relevant fields, when available, at which point guidelines can be established (Lu *et al.* 1999).

CASE STUDY

Evaluation of different disinfection approaches is crucial in assessing risk and cost trade-offs in the selection of a water treatment option. The management for drinking disinfections is generally based on human health risks from DBP exposure, cost, technical feasibility and disinfection performance. In this study, human health risk was assessed using THM in Newfoundland's drinking water. The Department of Environment and Conservation (DOE), Newfoundland, Canada published THM data from 451 water supply systems, in which 113 treatment plants (25% of the total) have been reported to have more than 100 μg/L (Canadian guideline's limitations) of total trihalomethanes (DOE 2006). The overall average is 78.4 μg/L with range of 0.68–434.8 μg/L, while excluding the zero valued rows, the average is 96.9 μg/L. Apparently, this might be the exceptional province in Canada, where average THM in drinking water is extremely high (DOE 2006). Kolla (2004) and Kar (2000) collected samples for component wise laboratory analyses from several locations near St. John's, NL, where they have reported minor differences. These differences may be due to sampling locations, extraction procedure, storage and capability of the analytical instruments, while Kolla used micro electron capture detector (μ-ECD) equipped with gas chromatography. The component wise findings from Kolla (2004) are shown in Table 2. For cancer and non-cancer risk assessment, the procedure described in

USEPA (1998) was employed as:

$$CDI = \frac{C_w IFD}{WT} \quad (7)$$

where,

CDI = chronic daily intake (mg/kg/day)
Cw = concentration of THM component in drinking water (mg/l)
I = drinking water ingestion rate (2 l/day for residents)
F = exposure frequency (365 days/year for residents)
D = exposure duration (77.1 years for Newfoundland (Statistics Canada 2005))
W = average body weight (70 kg)
T = averaging time (77.1 × 365 = 28141 days for Newfoundland (Statistics Canada 2005))

$$Cancer\,Risk = CDI \times SF \quad (8)$$

where,

SF = slope factor ([mg/kg/day]$^{-1}$)

The non-carcinogenic effect defined as hazard quotient is calculated as

$$Hazard\,Quotient = \frac{CDI}{R_f D} \quad (9)$$

where

$R_f D$ = reference dose (mg/kg/day)

The cost for chlorination was found to be the lowest among the three disinfection approaches followed by chloramination and GAC with post chlorination (Clark *et al.* 1994, 1998; Reiff 1995; Chowdhury & Husain 2006). Technical feasibility of a disinfection approach also depends on the ease of operation, maintenance and technology availability. The ease of operation, availability of the technology and maintenance of chlorination were found to be better in comparison to the other available technologies and the technical feasibility was assumed from expert judgments (MOE 2004; DOE 2005; Chowdhury & Husain 2006). The ultimate disinfection performances for the three disinfection approaches were found to be comparable for each of the disinfection methods (Lykins *et al.* 1994).

The hierarchy framework (Figure 3) illustrates the breakdown of the generalized attributes into basic attributes. The basic attributes for different approaches are shown in Table 3. Cancer and non-cancer risks have been presented on a log-scale (Table 3) to capture their low values. Fuzzy scales for different basic attributes are shown in Table 4 . The basic attributes were characterized by TFNs with minimum, most likely and maximum values to capture the associated uncertainties (Table 3). To fuzzify the basic attributes, fuzzy data were mapped into the fuzzy scales and respective membership grades were determined with respect to μ_1(worst), μ_2(bad), μ_3(poor), μ_4(fair), μ_5(good) and μ_6(best). Figures (5–9) show mappings of different basic attributes. For example, the fuzzy set for cancer risk (a_{111}) was found to be (0, 0.39, 0.89, 0.65, 0.25, 0) from Figure 5 and Table 3.

In defining priorities for the attributes at each level, pair-wise comparison (Saaty 1988) was employed. At the highest level (Level 2), disinfection efficiency was assigned two times the priority of the risk from exposure to DBP (Table 6) because of the increased concern for human health protection if exposed to improperly disinfected water (IPCS 2000). Cost was given equal priority to the health risk

Table 2 | THMs in tap water of the communities in Newfoundland (source: Kolla 2004)

Compounds	Minimum (mg/l)	Most likely (mg/l)	Maximum (mg/l)	RfD mg/kg/day	SF (mg/kg/day)$^{-1}$
Chloroform	0.0194	0.121	0.2831	0.01	0.01
Bromodichloromethane	0.001	0.002	0.0061	0.02	0.062
Bromoform	0.0001	0.0005	0.0010	0.02	0.0079
Dibromochloromethane	0.0039	0.0079	0.0186	0.02	0.0084

Table 3 | Input variables for basic attributes (Kolla 2004; Chowdhury & Husain 2006)

Basic Attributes	Identification	Chlorination	GAC with post chlorination	Chloramine
a_{111}	Cancer risk (log-scale)	−11.7, −10.2, −9.3	−14.3, −13, −12.5	−12.5, −11, −10
a_{112}	(Non-Cancer risk (log-scale)	−2.8, −1., −0.17	−3, −15, −0.5	−2.5, −1.25, −0.3
a_{211}	Technology Cost ($ Person/year)	0.12, 0.4, 0.8	0.3, 0.6, 1.0	0.2, 0.5, 0.9
a_{212}	Operation Cost ($ Person/year)	0.1, 0.12, 0.15	0.15, 0.25, 0.4	0.12, 0.15, 0.18
a_{213}	Maintenance Cost ($ Person/year)	0.05, 0.09, 0.12	0.1, 0.2, 0.35	0.08, 0.12, 0.25
a_{311}	Ease of Operation	0.7, 0.8, 0.9	0.5, 0.6, 0.7	0.6, 0.7, 0.8
a_{312}	Technology availability	0.75, 0.85, 0.95	0.5, 0.6, 0.8	0.55, 0.7, 0.8
a_{313}	Ease of Maintenance	0.6, 0.75, 0.9	0.5, 0.64, 0.7	0.55, 0.65, 0.8
a_{411}	In distribution system	0.7, 0.85, 0.99	0.7, 0.85, 0.99	0.5, 0.7, 0.9
a_{412}	In treatment plant	0.7, 0.8, 0.9	0.7, 0.91, 0.97	0.65, 0.75, 0.85
a_{421}	Taste/Odor removal	0.6, 0.7, 0.9	0.7, 0.85, 0.98	0.75, 0.85, 0.96
a_{422}	Color Removal	0.6, 0.7, 0.9	0.7, 0.84, 0.95	0.6, 0.7, 0.8

Table 4 | Fuzzy scales for basic attributes with triangular fuzzy numbers

Basic Attributes	Nomenclature	Worst (μ_1)	Bad (μ_2)	Poor (μ_3)	Fair (μ_4)	Good (μ_5)	Best (μ_6)
a_{111}	Cancer risk (log-scale)	−9, −8, >−8	−10, −9, −8	−11, −10, −9	−12, −11, −10	−13, −12, −11	<−13, −13, −12
a_{112}	(Non-Cancer risk (log-scale)	−9, −8, >−8	−10, −9, −8	−11, −10, −9	−12, −11, −10	−13, −12, −11	<−13, −13, −12
a_{211}	Technology Cost ($ Person/year)	0.8, 1.0, >1.0	0.6, 0.8, 1.0	0.4, 0.6, 0.8	0.2, 0.4, 0.6	0, 0.2, 0.4	<0, 0, 0.2
a_{212}	Operation Cost ($ Person/year)	0.8, 1.0, >1.0	0.6, 0.8, 1.0	0.4, 0.6, 0.8	0.2, 0.4, 0.6	0, 0.2, 0.4	<0, 0, 0.2
a_{213}	Maintenance Cost ($ Person/year)	0.8, 1.0, >1.0	0.6, 0.8, 1.0	0.4, 0.6, 0.8	0.2, 0.4, 0.6	0, 0.2, 0.4	<0, 0, 0.2
a_{311}	Ease of Operation	0, 0, 0.2	0, 0.2, 0.4	0.2, 0.4, 0.6	0.4, 0.6, 0.8	0.6, 0.8, 1	0.8, 1, 1
a_{312}	Technology availability	0, 0, 0.2	0, 0.2, 0.4	0.2, 0.4, 0.6	0.4, 0.6, 0.8	0.6, 0.8, 1	0.8, 1, 1
a_{313}	Ease of Maintenance	0, 0, 0.2	0, 0.2, 0.4	0.2, 0.4, 0.6	0.4, 0.6, 0.8	0.6, 0.8, 1	0.8, 1, 1
a_{411}	In distribution system	<0.4, 0.4, 0.5	0.4, 0.5, 0.6	0.5, 0.6, 0.7	0.7, 0.8, 0.9	0.8, 0.9, 1.0	0.9, 1, 1
a_{412}	In treatment plant	<0.4, 0.4, 0.5	0.4, 0.5, 0.6	0.5, 0.6, 0.7	0.7, 0.8, 0.9	0.8, 0.9, 1.0	0.9, 1, 1
a_{421}	Taste/Odor removal	<0.4, 0.4, 0.5	0.4, 0.5, 0.6	0.5, 0.6, 0.7	0.7, 0.8, 0.9	0.8, 0.9, 1.0	0.9, 1, 1
a_{422}	Color Removal	<0.4, 0.4, 0.5	0.4, 0.5, 0.6	0.5, 0.6, 0.7	0.7, 0.8, 0.9	0.8, 0.9, 1.0	0.9, 1, 1

Table 5 | Fuzzified sets of basic attributes for different treatment technology

	Chlorination	GAC with post chlorination	Chloramine
$a_{ij\ k}$	[μ_1, μ_2, μ_3, μ_4, μ_5, μ_6]	[μ_1, μ_2, μ_3, μ_4, μ_5, μ_6]	[μ_1, μ_2, μ_3, μ_4, μ_5, μ_6]
a_{111}	[0, 0.39, 0.89, 0.65, 0.25, 0]	[0, 0, 0, 0, 0.37, 1]	[0, 0, 0.5, 1, 0.6, 0.15]
a_{112}	[0.45, 1, 0.62, 0.33, 0, 0]	[0.25, 0.75, 0.77, 0.43, 0, 0]	[0.36, 0.88, 0.65, 0.24, 0, 0]
a_{211}	[0, 0.37, 0.7, 1.0, 0.61, 0.212]	[0.35, 0.66, 1.0, 0.59, 0.21, 0]	[0.2, 0.5, 0.5, 0.83, 0.4, 0]
a_{212}	[0, 0, 0, 0, 0.67, 0.48]	[0, 0, 0, 0.6, 0.73, 0.17]	[0, 0, 0, 0, 0.86, 0.34]
a_{213}	[0, 0, 0, 0, 0.54, 0.66]	[0, 0, 0, 0.45, 1.0, 0.34]	[0, 0, 0, 0.17, 0.78, 0.49]
a_{311}	[0, 0, 0, 0.35, 1.0, 0.46]	[0, 0, 0.34, 1.0, 0.34, 0]	[0, 0, 0, 0.67, 0.67, 0]
a_{312}	[0, 0, 0, 0.17, 0.9, 0.54]	[0, 0, 0.34, 1.0, 0.5, 0]	[0, 0, 0.14, 0.71, 0.67, 0]
a_{313}	[0, 0, 0, 0.55, 0.91, 0.35]	[0, 0, 0.3, 0.9, 0.34, 0]	[0, 0, 0.16, 0.76, 0.62, 0]
a_{411}	[0, 0, 0, 0.35, 0.92, 0.55]	[0, 0, 0, 0.35, 0.92, 0.55]	[0, 0, 0, 0.3, 0.76, 0.25]
a_{412}	[0, 0, 0, 0.37, 1.0, 0.37]	[0, 0, 0, 0.41, 0.93, 0.55]	[0, 0, 0, 0.5, 0.81, 0.1]
a_{421}	[0, 0, 0, 0.66, 0.75, 0.25]	[0, 0, 0, 0.46, 0.96, 0.59]	[0, 0, 0, 0.25, 0.76, 0.6]
a_{422}	[0, 0, 0, 0.66, 0.75, 0.25]	[0, 0, 0, 0.56, 0.94, 0.65]	[0, 0, 0, 0.68, 0.7, 0]

as extrapolated from expert judgments (Sadiq *et al.* 2004). The hierarchy structure in Figure 3 was followed to provide the aggregation of the basic attributes into more generalized attributes. In this case study at level 2, the following fuzzy sets were obtained for the different attributes

$$Human\,health\,risk(a_1) = (0.11, 0.38, 0.68, 0.65, 0.21, 0.00)$$

$$Cost(a_2) = (0.00, 0.19, 0.37, 0.53, 0.61, 0.38)$$

$$Technical\,feasibility(a_3) = (0.00, 0.00, 0.00, 0.33, 0.95, 0.46)$$

$$Disinfection\,performance(a_4) = (0.00, 0.00, 0.00, 0.42, 0.91, 0.44)$$

The final fuzzy set obtained for chlorination is expressed as:

$$System\,Index(chlorination) = (0.01, 0.06, 0.12, 0.25, 0.37, 0.18)$$

The *System Indices* of the other two disinfectants were evaluated in a similar manner and found as:

$$System\,Index(GAC\,with\,chlorination) = (0.02, 0.06, 0.14, 0.31, 0.33, 0.14)$$

$$System\,Index(chloramination) = (0.06, 0.15, 0.12, 0.25, 0.34, 0.08)$$

The normalized membership grades for each of the scales-worst, bad, poor, fair, good and best, for each disinfectant option are represented in Figure 10. The utility values were determined by using Equation (6). Following the optimistic approach as described previously, the utility function values were computed to be $U_{a(chlorination)} = 5.34$, $U_{a(GACwithchlorination)} = 5.0$ and $U_{a(chloramination)} = 4.28$.

The ranks of chlorination, granular activated carbon with post chlorination and chloramination are 1, 2 and 3 respectively. This ranking order may be sensitive to the weights and fuzzy scaling system; thus, sensitivity analyses should be performed. The weighting schemes were varied as shown in Table 6 in different trials to perform the sensitivity

Table 6 | Weighing schemes of different hierarchy level attributes

$a_{ij\,k}$	W_3	a_{ij}	W_2	a_i	W_1 (T_1)	W_1 (T_2)	W_1 (T_3)	W_1 (T_4)	W_1 (T_5)
a_{111}	0.714	a_{11}	1.00	a_1	0.214	0.233	0.333	0.4	0.25
a_{112}	0.286								
a_{211}	0.526	a_{21}	1.00	a_2	0.214	0.186	0.165	0.1	0.25
a_{212}	0.263								
a_{213}	0.211								
a_{311}	0.484	a_{31}	1.00	a_3	0.143	0.116	0.165	0.1	0.25
a_{312}	0.322								
a_{313}	0.194								
a_{411}	0.67	a_{41}	0.8	a_4	0.428	0.465	0.333	0.4	0.25
a_{412}	0.33								
a_{421}	0.55	a_{42}	0.2						
a_{422}	0.45								

analysis. After five trials, the analyses showed that the chlorination was ranked as the best option in all the other trials except the fourth trial. The choice of different weighting schemes is arbitrary and a guideline can be set through expert opinions (Lee 1992; Sadiq *et al.* 2004; Chowdhury & Husain 2006).

SUMMARY AND CONCLUSIONS

Naturally occurring organic matter (NOM) and disinfectants are primarily responsible for DBP formation in drinking water. The use of ozonation and ultraviolet ray (UV) radiation can minimize regulated DBP formation, but

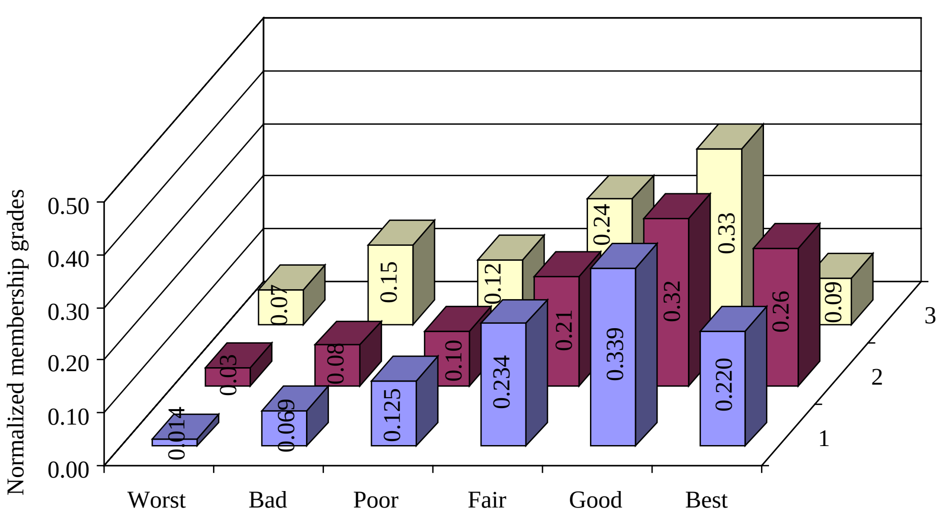

Figure 10 | Final normalized fuzzy ranking (Trial 1).

Table 7 | Summary of the results

Trial No.	Treatment	μ_1	μ_2	μ_3	μ_4	μ_5	μ_6	Ua	Rank
W_1	**Chlorination**	**0.01**	**0.06**	**0.12**	**0.25**	**0.37**	**0.18**	**0.534**	**1**
	GAC with post chlorination	0.02	0.06	0.14	0.31	0.33	0.14	0.500	2
	Chloramine	0.06	0.15	0.12	0.25	0.34	0.08	0.428	3
W_2	**Chlorination**	**0.01**	**0.07**	**0.12**	**0.26**	**0.37**	**0.18**	**0.531**	**1**
	GAC with post chlorination	0.02	0.05	0.13	0.31	0.34	0.15	0.511	2
	Chloramine	0.07	0.15	0.12	0.24	0.33	0.09	0.425	3
W_3	**Chlorination**	**0.02**	**0.08**	**0.15**	**0.26**	**0.33**	**0.15**	**0.496**	**1**
	GAC with post chlorination	0.02	0.06	0.16	0.34	0.31	0.11	0.476	2
	Chloramine	0.09	0.19	0.16	0.23	0.28	0.06	0.374	3
W_4	Chlorination	0.02	0.09	0.16	0.27	0.32	0.14	0.479	2
	GAC with post chlorination	**0.01**	**0.06**	**0.15**	**0.33**	**0.33**	**0.13**	**0.495**	**1**
	Chloramine	0.10	0.22	0.17	0.20	0.26	0.06	0.358	3
W_5	Chlorination	**0.01**	**0.07**	**0.14**	**0.25**	**0.35**	**0.17**	**0.517**	**1**
	GAC with post chlorination	0.02	0.07	0.17	0.35	0.29	0.09	0.451	2
	Chloramine	0.07	0.17	0.14	0.26	0.30	0.06	0.394	3

ozonation can form some more harmful (bromate) and unregulated DBP. They also require secondary disinfection to protect the distribution systems. These applications are often costly and require extensive monitoring. In trade-off studies, each of the basic attributes affecting the decision making process are considered. The experts (researchers, decision-makers, regulators) in the relevant fields establish priorities for each attribute. These are then carried over following a standard procedure for the assessment of the best disinfection approach for which, to illustrate the case study presented in this paper, fuzzy hierarchy aggregation was employed.

In the first trial, the risk associated with DBP exposure was given equal priority to the cost (Table 6). The chlorination was ranked as the approach of choice (Table 7). In this trial, the technical feasibility was given a lower priority than cost. The disinfection performance was given two times the priority than the risk from exposure to DBP (Table 6). In the second trial, the risk associated with DBP exposure was assigned higher priority than cost and technical feasibility and disinfection performance was given two times the priority (Table 6) than the risk from DBP exposure. Under this scenario, chlorination was ranked as the option of choice (Table 7). In the third trial, risk from exposure to DBP was given equal priority to the disinfection performance and twice priority than the cost and technical feasibility. Chlorination was again ranked as the preferred option (Table 7). In the fourth trial, risks from DBP exposure and disinfection performance were given a much higher priority, but cost and technical feasibility were given equal priority. GAC with post chlorination was ranked as the best option. The assignment of weighting schemes was found to be a sensitive parameter in the evaluation of disinfection approaches (Table 7). In the fifth trial, each parameter was assigned equal priority. In this case, chlorination was ranked as the first option once again.

The fuzzy based evaluation through hierarchy structure involves identification and fuzzification of the basic attributes, assigning relative weights, aggregation through hierarchy structure, defuzzification and ranking of management alternatives. The fuzzified values of each basic attribute were grouped using hierarchy structure. The final fuzzy sets were defuzzified and utility function values were evaluated to determine their ranking order. The weighting schemes were developed using AHP. The reduction of risk from microbial contamination was given higher priority to ensure human health protection from waterborne diseases. By assigning different weighting schemes, five trials were performed to verify the impact of different weighting schemes on the system indices. The evaluation was found to be sensitive to the assignment of weighting schemes.

Human judgments are associated in the fuzzy evaluation process. Thus, there is a possibility of biases. The bias due to subjective information can be reduced through incorporation of more than one expert in the relevant field. A Delphi type study can be performed until a consensus is achieved. The assignment of weighting schemes was performed in crisp values for simplicity, which may be in interval other than a single value. In such case, the max-min paired elimination method through fuzzy α-cut technique can be employed. The data associated with this study was imprecise in general. If precise data is available, this framework may provide a better understanding for the decision-making process. The application of fuzzy synthetic evaluation can be extended to similar types of environmental management studies such as water quality issues, solid waste management, produce water discharges from offshore oil and gas platforms, etc. However, this application requires representative information in qualitative and/or quantitative terms from experts in the relevant fields.

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