Reconciling 'actual' risk with 'perceived' risk for distributed water quality: a QFD-based approach

Alex Francisque, Manuel J. Rodriguez, Rehan Sadiq, Luis F. Miranda and François Proulx

ABSTRACT

This paper explores the application of the quality function deployment (QFD) approach to identify and prioritize factors to reconcile 'actual' risk with 'perceived' risk for drinking water in a distribution network. Consumers' complaints (regarding water odour, taste, colour and other problems) and consumers' perception about water safety are used to define customers' requirements (aka 'whats'). Twelve water quality parameters and distribution network properties (e.g. turbidity, pipe breaks) are used as indicators for drinking water quality – the product characteristics (aka 'hows'). Correlations between 'whats' and 'hows' are established using data obtained from a case study. Opinions of experts in drinking water and consumers are used to define correlations between the 'what' 'microbial safety' and the 'hows'. The analytic hierarchy process allows prioritizing customer requirements. Three QFD-based methods are applied to prioritize factors affecting water quality in a distribution network. The proposed approach is demonstrated through a case study of a water distribution network in Quebec City (Canada). Results show that the factors that primarily affect customers' requirements include free residual chlorine, turbidity and trihalomethanes. Sensitivity analyses using three scenarios confirm the robustness of the proposed approach. Utility managers must take action, especially concerning these product characteristics, to satisfy customers' requirements.

Key words | customer expectations and perception, distribution network, drinking water, quality function deployment (QFD), risk, water quality

Alex Francisque
Rehan Sadiq
Okanagan School of Engineering,
The University of British Columbia,
3333 University Way,
Kelowna, BC, Canada, V1V 1V7

Manuel J. Rodriguez (corresponding author)
École Supérieure d'Aménagement du Territoire,
Université Laval, 1628 Pavillon Savard,
Université Laval,
Québec City, QC, Canada, G1K 7P4
E-mail: *manuel.rodriguez@esad.ulaval.ca*

Luis F. Miranda
Department of Civil Engineering and Applied
Mechanics,
McGill University,
817 Sherbrooke Street West,
Montreal, QC, Canada, H3A 2K6

François Proulx
Division de la Qualité de l'Eau,
Service de l'Environnement,
Ville de Québec, 1595,
Mgr Plessis,
Québec City, QC, Canada, G1M 1A2

INTRODUCTION

Supply of safe drinking water to consumers involves many stages. First, the raw water is drawn either from a surface source (catchment basin) or from a groundwater aquifer. Next, the treatment plant treats the raw water through various unit processes, depending on raw water quality and drinking water standards. Finally, the finished water is supplied to consumers through a distribution network (DN) that may consist of hundreds of kilometres of pipes. In addition, the water quality in the DN is regularly monitored at various designated locations.

Municipalities invest heavily to assure that the supplied water complies with quality standards, regulations and/or guidelines. Recently, however, many people have started using bottled water as an alternative to tap water. According to the International Bottled Water Association (2009), consumption of bottled water in the world increased from 38.11 billion to 52.7 billion gallons (G) from 2003 to 2008. In the United States in particular, the average annual increase from 2000 (4.72 billion G) to 2008 (8.67 billion G) was almost 10%; that is, per capita, a jump from 16.7 to 28.5 G. Paradoxically, tap water quality has improved significantly throughout North America due to stringent regulatory regimes and availability of improved treatment technologies. The USEPA (2001) reports that only 5% of water treatment systems have

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ever exceeded any USEPA maximum contaminant level (MCL).

The increase in the use of alternatives to municipal tap water is directly related to customer perceptions about water quality in the DNs (Mackey *et al.* 2003). It can also be linked to customer expectations and water utility priorities. Customers are obviously concerned about the safety of drinking water and generally they have near zero level tolerance for taste, odour or appearance. According to Kirmeyer *et al.* (2000), customers' principal expectations in the order of priority are:

1. a safe product that meets regulations (at various levels: federal, state, etc.);
2. a product free of excess residual chlorine;
3. a product free of taste and odour;
4. a product with good appearance (in terms of colour); and
5. uniform quality of tap water.

However, the main priorities of water utilities include (Kirmeyer *et al.* 2000):

1. 'microbial safety' of distributed water;
2. maintenance of a sufficient disinfectant residual;
3. taste and odour removal and prevention;
4. corrosion control; and
5. minimization of disinfection by-product formation.

It is obvious that a level of residual disinfectant considered sufficient for the utility may be excessive for the consumer. For example, for another DN in Quebec City, Proulx *et al.* (2010) concluded that the public perceived a risk about excess of free residual chlorine for concentrations above 0.65 mg/L. The average concentration of free residual chlorine in the latter DN was 1.5 mg/L whereas it is only 0.5 mg/L in DN investigated in this paper. Consequently, the concentration for which the consumer in the actual DN would perceive a similar risk could be estimated to be between 0.4 and 0.6 mg/L. The results of a recent USA survey suggest that the perception of taste (e.g. musty/earthy, metallic and chlorinous) is a major driver for the use of bottled drinking water (Mackey *et al.* 2003). Consequently, it is crucial for water utilities to align their priorities with customer expectations and maintain user trust in tap water. To achieve this, it is necessary to develop strategies and approaches that can reconcile the risk 'perceived' by the consumers with the 'actual' risk incurred by the consumption of tap water. In other words, it is important for utilities to supply drinking water with good quality and also improve consumers' confidence and perception about the quality of supplied drinking water.

This paper presents an innovative application of quality function deployment (QFD) to identify and prioritize technical factors related to management (monitoring and maintenance) of DN that can be linked to the factors contributing to the risk perceived by the customer. First, the QFD approach will be introduced and followed by an application in management of drinking water quality. Afterwards, sensitivity analysis results, including a final discussion, will be presented, followed by the main conclusions of this research.

QUALITY FUNCTION DEPLOYMENT

Definition of concepts

Quality in the context of the success of a product can be defined as a multi-attribute function involving any element that makes a product more desirable for the customer (Garvin 1987; Huthwaite 1988; Franceschini & Rossetto 1995; Galetto 1996). Innovation related to quality is recognized as any intervention that can modify the market, even marginally (Villa *et al.* 1991). According to Franceschini (2002), there are three types of quality: perceived, offered and expected quality. Perceived quality (Q_p) of a product, for example distributed drinking water, is the effect of innovation on a product transformed by the customer in a set of attributes (e.g. less or no taste, no odour, better appearance). Offered quality (Q_o) is the quality that is actually assured (distributed water with apparent colour below 15 TCU, without pathogens, turbidity below 1 NTU, etc.) by the producer (water utility managers) through different operations.

As a rule, Q_p and Q_o are not equal for two reasons: information asymmetries and different metrics used to evaluate product attributes. Customer evaluation is based on a reference model that compares different products and is subject to the marketing pressure of all competitors. Generally, this model leads to *expected quality* (Q_a), (e.g. the expected quality of tap water in comparison to bottled water), for which its changeable nature does not concur with the Q_p. Every enterprise, including drinking water purveyors, must direct efforts at modifying all three dimensions of quality in such a way that Q_o approaches both Q_p and Q_a. This will allow the preservation and increase in market share (i.e. tap water consumers) (Franceschini 2002). Enterprises must also facilitate parallelism in the design both for the product (tap water) and for its manufacturing or production processes. To achieve this, hardware and software tools and various methodologies such as quality function deployment (QFD) have been developed (Franceschini 2002).

Brief history and usefulness of QFD

The QFD approach was initiated in 1967 in Japan. By the end of the 1970s, QFD became very popular, owing to the work of Yoji Akao (Franceschini 2002). It is a tool in which responsibilities for producing a quality item (in our case distributed drinking water) must be assigned to all parts of a corporation (Akao 1989). For drinking water managers, these include source water protection, water treatment plant operation and management, water distribution and routine quality monitoring in the DN. QFD guarantees that customer requirements are heeded from the beginning when decisions concerning product characteristics are made (Akao 1986). QFD is a functional planning tool used to ensure that the *voice of the customer* is deployed throughout product planning and design steps (Franceschini 2002).

QFD involves two fundamental aspects: *customer requirements* and *design (or production) specifications*. Customer requirements are usually expressed in terms of qualitative characteristics broadly defined (e.g. safe water, free of excess residual chlorine, free of taste and odour, with good appearance and uniform quality). Design specifications are the successive conversion of customer needs during product development into internal company requirements, usually measurable characteristics (absence of pathogens or faecal coliforms, turbidity levels below 1 NTU, pH between 6.5 and 8.5, at least 0.3 mg/L of free residual chlorine at the exit of the treatment plant, water colour below 15 TCU, HPC bacteria less than 500 cfu/mL, for example, in North America). The philosophy governing the application of QFD places the emphasis on both *what* needs to be done and *how* it can be done (Conti 1989).

QFD originated in manufacturing where it has been used for many decades (Garvin 1987; Franceschini 2002). However, QFD has become very popular in several other domains. For instance, QFD has been applied in aerospace (Kojima *et al.* 2007; Pica *et al.* 2008), defence (Bergman 2008; Kirkpatrick *et al.* 2008; Stansfield & Cole 2008), public transportation (Hopwood II & Mazur 2007), education (Chan *et al.* 2007; Durán 2007; Prusak 2007), lifecycle analysis (Cheema & Hussain 2007; Nakamura 2007), logistics (Crostack *et al.* 2007), the process industry (Lager & Kjell 2007), telecommunications (de Souza *et al.* 2007; Xiong & Xia 2007) and health care (Hepler & Mazur 2008). In environmental management, applications of QFD are recent and have focused on using extended approaches known as Eco-QFD to combine environmental issues and costs with stakeholder requirements (Zhang *et al.* 1999; Mehta & Wang 2001; Ernzer *et al.* 2003; Masui *et al.* 2003; Utne 2009). However, QFD has never been applied in the area of drinking water management.

House of quality (HoQ)

The house of quality (HoQ) is the first matrix to be used in QFD. Its purpose is to describe the basic process underlying QFD: the transition from a list of customer requirements, or 'what', to a list of considerations (product characteristics, technical characteristics or design requirements) concerning 'how' the requirements will be met (Franceschini 2002). Figure 1 presents the outline and different parts of the HoQ that include:

- *Customer demands or 'whats'* (Part 1): The 'whats' are the list of basic customer needs usually expressed in vague and imprecise terms (e.g. safe water, free of excess residual chlorine, taste and odour, good appearance and uniform quality). The terms 'customer demands', 'customer needs', 'customer requirements' and 'whats' are interchangeably used in this paper.
- *Design characteristics or 'hows'* (Part 2): The 'hows' represent product or technical characteristics that help to meet 'whats'. The terms 'design characteristics', 'product characteristics', 'technical characteristics' and 'hows' are interchangeably used in this paper.

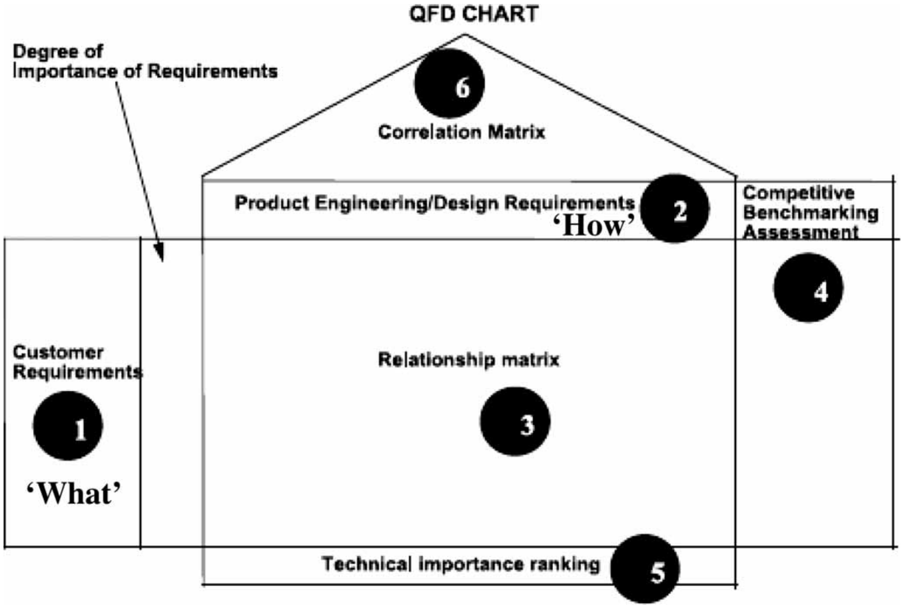


Figure 1 | Principal components of the House of Quality (modified after Franceschini 2002).

- *Relationship matrix* (Part 3): This relates to how product characteristics or decisions affect the satisfaction of each customer need. The matrix consists of relationships between customer demands and each product characteristic.
- *Competitive benchmarking assessment* (Part 4): This allows a comparison between the product to be produced (e.g. distributed drinking water) and other products of the same type (e.g. bottled water). For brevity this component is not studied here.
- *Product or technical characteristic importance ranking* (Part 5): This will contain the results of the prioritization of product characteristics to satisfy customer requirements. It represents the impact of each product characteristic on the customer demands.
- *Correlation matrix* (Part 6): The roof of the HoQ represents the interdependencies among 'hows'. It can play an important role in deciding on the number of 'hows' that directly affect the economics.

Methods for prioritizing 'whats' and 'hows'

To satisfy the customers, their needs must be prioritized, i.e. the level of relative importance of various 'whats' must be determined. Different approaches exist to prioritize 'whats'; however, in this study analytic hierarchy process (AHP) is used and described later in detail. Once 'whats' are determined and prioritized, it is important to decide how to obtain the desired results, i.e. how to satisfy customers' needs. Determination of 'hows' implies translating customers' needs expressed in subjective terms into objective factors of a technical nature (e.g. levels of free residual chlorine, turbidity, temperature, colour). These characteristics are indeed a product or service description expressed in designer (i.e. water utility manager) language. It involves establishing a list showing the 'hows' with at least one 'how' for each 'what'. Product characteristics represent the offered quality (Q_o) demonstrated through a product or service description provided in measurable terms, and should directly affect customer perception of quality (Franceschini 2002). However, before prioritizing 'hows', it is important to indicate how these characteristics affect the satisfaction of each 'what', i.e. to fill the relationship matrix.

The HoQ relationship matrix must be completed using correlations defined between each 'what' and each 'how'. Three elements determine the importance of 'hows': the importance of 'whats' to which the 'how' is correlated, the level of correlation (e.g. *weak*, *medium*, *strong*) and the degree of difficulty its implementation entails (Franceschini 2002). In this study, three methods are used for the prioritization of product characteristics ('hows'). The absolute weight of each product characteristic ('how') is determined as shown by Equation (1) (Franceschini 2002):

$$w_j = \sum_{i=1}^{n} d_i \cdot r_{ij} \tag{1}$$

where w_j is the technical importance rating (absolute weight) of the j-th product characteristic (e.g., turbidity), d_i is the *degree of relative importance* of the i-th customer requirement ('what') (e.g., water with good appearance, no colour), r_{ij} is the cardinal relationship between the i-th customer requirement and the j-th product characteristic, $i=1, 2, \ldots, n$; $j=1, 2, \ldots, m$; n is the number of 'whats' and m is the number of 'hows'. The main difference between these methods lies in the way r_{ij} is calculated:

(i) *Independent scoring method* is the classical QFD method (Akao 1988). Cardinal relationships r_{ij} constituting the relationship matrix are not normalized. This method presents a major drawback in certain cases. It can assign a weak relative importance to some 'hows' (e.g. free residual chlorine) that have a *strong* correlation with some 'whats' more important for the customer (e.g. 'microbial safety') and vice versa. It depends on the way the product characteristics ('hows') are defined, i.e. if they are subdivided into sub-characteristics or not.

(ii) *Lyman's normalization method* (Lyman 1990) tries to resolve the issues related to the independent scoring method by normalizing the coefficients r_{ij} in the relationship matrix. The normalized coefficient $\tilde{r}_{ij}$ is of this form:

$$\tilde{r}_{ij} = \frac{r_{ij}}{\sum_{j=1}^{m} r_{ij}} \tag{2}$$

(iii) *Wasserman's normalization method* (Wasserman 1993) is an extension of Lyman's method that considers in the normalization process interdependence between product characteristics, i.e. the correlation matrix (the roof of the HoQ). The expression of the normalized coefficient $r_{i,j}^{norm}$ is as follows:

$$r_{i,j}^{norm} = \frac{\sum_{k=1}^{m} \left(r_{i,k} \cdot \gamma_{k,j} \right)}{\sum_{j=1}^{m} \sum_{k=1}^{m} \left(r_{i,j} \cdot \gamma_{j,k} \right)} \tag{3}$$

where γ_{jk} is the intensity of the correlation between product characteristic j (e.g., water turbidity) and product characteristic k (e.g., water colour).

AN APPLICATION OF QFD: MANAGEMENT OF DRINKING WATER QUALITY

In our extensive literature search, we found that QFD has never been applied before in the management of drinking water quality. Drinking water is equated to a 'product', and, obviously, consumers have a certain perception about its quality (perceived quality, Q_p) leading to certain requirements or needs (expected quality, Q_a). Utility managers may have solutions to these requirements (offered quality, Q_o). Thus, QFD can be applied to conciliate consumer and management requirements related to drinking water quality.

Case study

A case study of a DN in Quebec City (Canada) serving nearly 240,000 people was considered. The treatment plant that feeds into this DN draws raw water from the St Charles River. Before distribution, the water is subjected to a chain of treatment processes consisting of coagulation, flocculation, sedimentation, slow sand filtration, ozonation and post-chlorination.

Unit of analysis

Water quality parameters vary continuously both spatially and temporally within a DN, from the point of exit of a treatment plant to the consumer tap (Francisque *et al.* 2009a). The consumer perception about distributed water may also change within a DN from one location to another. For these reasons, the area served by the studied DN was divided into 52 zones, where each zone corresponds to a sector of influence of one monitoring location. For each zone, all parameters related to basic customer demands ('whats') and to technical characteristics ('hows') are documented. The dissemination area (DA) was considered as a geographic unit in which 'whats' and 'hows' attributes should be documented. A DA is a small, relatively stable, geographic unit composed of one or more adjacent dissemination blocks. It is the smallest standard geographic area for which all census data in Canada are disseminated. DAs are uniform in terms of population size, which is targeted from 400 to 700 persons to avoid data suppression. DAs cover all the territory of Canada (Statistics Canada 2001). However, owing to the small size of the DAs, they were combined to obtain one monitoring location per sector or zone. A zone is an area of the DN formed by one or several DAs and contains at least one monitoring location. Using a geographic information system (GIS), each DA lacking a monitoring location was joined to the adjacent DA containing one, based on the distance from its centroid to the monitoring location.

Definition of customer requirements and product characteristics

The 'whats'

Customer requirements are the list of basic demands that play a major role in the QFD approach. In this case, the customers are consumers who use drinking water supplied through the DN. Customers require *safe* drinking water, free of excess residual chlorine, with no taste, no odour and no poor appearance (Kirmeyer *et al.* 2000). To consider customer requirements, i.e. customer expected quality (Q_a) from tap water in relation to customer perceived quality (Q_p), consumer complaints were inventoried. For each zone, four types of consumer complaints were recorded (2002–2007) by the utility and documented for summer, winter and for the four seasons combined (global data). Data for winter and summer (two extreme seasons) were considered because consumer perception regarding distributed drinking water quality varies temporally (Montenegro-Rousseau *et al.* 2009).

Customer complaints are categorized as *odour*, *colour*, *taste* and *other* (i.e. all complaints other than the first three). These complaints are used to determine 'whats', i.e. water free of excess residual chlorine, taste and odour, with good appearance and uniform quality. In addition, 'microbial safety' is added to this list. The following attributes are considered for 'whats':

- *Odour complaints:* odour-related complaints of distributed water;
- *Colour complaints:* complaints about the visible appearance (colour) of water;
- *Taste complaints:* taste-related complaints of distributed water;
- *Other complaints:* encompass all other types of consumer complaints related to distributed drinking water (e.g. particles, health problems that could be caused by the consumption of distributed water); and
- *'Microbial safety':* this refers to consumer expectations or needs to receive distributed water without any danger of microbial contamination. For this specific 'what', there is no defined process or protocol to account for consumer complaints. The correlation between this attribute and each 'how' is defined based on expert judgment. Further details on this 'what' attribute will be provided later.

The 'hows'

The design or technical characteristics constitute the second component of the HoQ. This represents the product's technical characteristics to meet customer requirements. A total of 12 'hows' were considered and divided into two types. The first type is related to water quality assessed during the routine monitoring program (i.e. 52 locations sampled on average every two weeks). These are known as *water quality parameters* that include: free residual chlorine, temperature, total trihalomethanes (TTHMs), turbidity, pH, colour, water ultraviolet absorbance at 254 nm (UV_254 nm) and heterotrophic plate count (HPC) bacteria. The other factors are *DN parameters* that refer to hydraulic and structural integrity characteristics such as water age, pipe material, pipe breaks and pipe age. Some of the parameters, particularly pipe breaks, pipe material, water temperature and free residual chlorine, have an important impact on the risk of water quality failures (Francisque

Table 1 | Statistical distribution of water quality parameters measured in the DN (2003–2005)

Parameters	*n*	Mean value	Standard deviation	Median	Mode	5th percentile	95th percentile
Free residual chlorine (mg/L)	3,595	0.50	0.313	0.50	0.60	<DL	1.0
Temperature (°C)	3,595	10.7	6.30	10.0	4.0	2.0	20.1
UV_254 nm (m^{-1})	3,595	2.74	0.888	2.60	2.48	1.80	4.20
pH	3,595	7.60	0.313	7.60	7.50	7.20	8.10
Turbidity (NTU)	3,595	0.33	0.30	0.30	0.20	0.10	0.73
Colour (TCU)	3,595	4.54	2.58	4	4	2	9
Faecal coliforms (cfu/100 mL)	3,592	0	0	0	0	0	0
Total coliforms (cfu/100 mL)	3,591	0.01	0.705	0	0	0	0
HPC (cfu/mL)	3,595	13.8	81.2	0	0	0	40

cfu: colony forming units; NTU: Nephelometric turbidity unit; TCU: unity of apparent colour; <DL: under the detection limit.
UV_254 nm: This parameter allows the estimation of natural organic matter content of the finished water. Some authors (van der Kooij *et al*. 1989; Kirmeyer *et al*. 2000), studying bacterial growth in drinking water DNs, observed a linear relationship between UV_254 nm and assimilable organic carbon.
Water colour: Thresholds for this parameter in drinking water are linked traditionally to criteria of aesthetic or organoleptic order. However, it was noticed that distributing coloured water could apparently cause tap water consumers to use other sources supplying less coloured water, without ensuring that they are safer for their health (Public Health Service 1962).
For all other parameters mentioned in this paper, see Francisque *et al*. (2009a, b) and Payment *et al*. (2003) for a complete description and their importance.

et al. 2009b). As the values of these parameters usually vary over time (Berry *et al*. 2006; Francisque *et al*. 2009a), the following cases were considered in the analysis: (1) winter, (2) summer and (3) the four seasons combined (global data).

The results in Table 1 highlight the fact that the system under study distributes high-quality water (offered quality, Q_o). Indeed, no faecal coliforms were detected during the period under study (likewise, very few cases of total coliforms were reported). In addition, turbidity and colour levels were found to be very low (only 2.6% of samples with turbidity higher than 1 NTU, and only 0.4% with colour higher than 15 TCU). For HPC bacteria, the observed levels were relatively low in comparison with levels reported by other studies (Delahaye *et al*. 2003; Hambsch *et al*. 2004).

Prioritizing customer requirements and product characteristics

Relationship matrix between 'whats' and 'hows'

Defining the relationship matrix is a fundamental step in the prioritization of 'whats' and 'hows'. The cardinal relationships r_{ij} between the *i*-th 'what' and the *j*-th 'how' are constituted by the square of Pearson's correlation coefficients. These coefficients are computed using the databases mentioned previously concerning 'whats' and 'hows'. In each of the 52 zones, the average number of consumers' complaints for each 'what', and the average value of measurements of each 'how', are used to compute the Pearson's correlation coefficients. However, for pipe breaks, the absolute number of breaks is used; and for pipe material, the percentage of metal pipe is considered in the analysis. Finally, for water age, due to lack of reliable data and to simplify the analysis, the hydraulic distance between the zone monitoring location and the water treatment plant or the water reservoir is used. Distances were assessed using a GIS (MapInfo 9.0). These relationships are defined, as required by the QFD approach, on a qualitative scale (1, 3, 9), i.e. *weak*, *medium* and *strong* correlations, respectively. By observing the distribution of real values in the relationship matrix, two different values were chosen, as cut-off values, to define three relatively homogeneous classes of correlation. Correlations lower than or equal to the first cut-off value are *weak*, correlations higher than the first cut-off value and lower than or equal to the second are assumed *medium* and the remaining are taken as *strong* correlations.

For the specific customer requirement 'microbial safety' (no database), a panel of experts was asked to define the relationship between this 'what' and each product characteristic. The same scale (1, 3, 9) was used by each panel member. Then the average value of the relationships (i.e. ~10 relationships because 10 experts were contacted) between the 'what' 'microbial safety' and the *j*-th 'how'

Table 2 | Relationship matrix between 'whats' and 'hows' for drinking water in Quebec City

Customer requirements ('whats')	Product characteristics (or technical characteristics or design requirements) ('hows') Water age	Pipe material	Pipe breaks	Pipe age	Free residual chlorine	Temperature	TTHMs	Turbidity	pH	Colour	UV_254	HPC
(a) Global data (four seasons combined)												
Odour	1	1	9	1	1	1	1	1	1	1	1	1
Colour	3	1	9	1	1	1	1	1	1	1	1	1
Taste	1	1	3	3	1	1	1	3	1	3	3	1
Other (particles, turbidity)	1	1	3	3	1	1	3	1	1	1	3	1
'Microbial safety'	3	1	3	1	9	3	1	3	1	1	1	1
(b) Summer data												
Odour	1	1	3	1	1	1	1	1	1	1	1	1
Colour	3	1	9	1	3	3	1	1	1	1	3	1
Taste	3	1	1	3	1	1	1	3	1	3	3	1
Other (particles, turbidity)	1	1	3	1	1	3	1	1	1	3	3	1
'Microbial safety'	3	1	3	1	9	3	1	3	1	1	1	1
(c) Winter data												
Odour	1	1	1	1	1	1	1	1	1	1	3	1
Colour	1	1	3	1	1	1	1	1	1	1	1	1
Taste	1	1	3	1	1	1	1	1	1	1	1	1
Other (particles, turbidity)	1	1	1	1	1	1	3	1	1	1	1	3
'Microbial safety'	3	1	3	1	3	3	1	3	1	1	1	1

was considered and mapped on the scale (1, 3, 9). This was carried out for global, winter and summer data.

The relationship obtained between each 'how' and each 'what' is presented in Table 2. Results show that the relationship between pipe breaks and odour is *strong* for global data (Table 2(a)), but *medium* for summer and winter (Tables 2(b) and 2(c)). Relationships between pipe breaks and water *colour* (in italics to avoid confusion with the 'how' having the same name), and between free residual chlorine and 'microbial safety', are also found to be *strong* both for global data (Table 2(a)) and summer data (Table 2(b)), and *medium* for winter data (Table 2(c)). The other relationships are *medium* or *weak*, particularly for winter data.

Prioritizing 'whats'

Customer requirements must be prioritized according to their preference. Franceschini (2002) suggests being absolutely certain that the *customer voice* and not the *designer voice* (treatment plant or utility manager) bears more weight in these matters. Therefore, it is necessary to determine the relative importance of each 'what' perceived by the customer (i.e. customer priority). The traditional QFD methodology assigns degrees of priority to 'whats' by using a scale from 1 (*negligible importance*) to 5 or 10 (*indispensable importance*). The analytic hierarchy process (AHP) developed by Saaty (1988) is one of the methods used to determine the level of importance assigned to the 'whats'. To describe the relative importance of requirements in a level (or group or category), a set of preference weights must be defined. These preference weights (w_i) are normalized to 1, as described by Equation (4) for n contributory factors of the group.

$$W = \sum_{i=1}^{n} w_i = 1\,; \quad 0 \le w_i \le 1 \tag{4}$$

The AHP uses pair-wise comparisons to estimate the preference weights (w_i) of each ‘what’ attribute. Saaty (1988) developed a table (see Francisque *et al.* 2009b) that provides a scale used to assign relative importance to customer requirements. The panel was asked to evaluate the degree of relative importance for each ‘what’ attribute using pair-wise comparison. Matrix A (Equation (5)) represents the pair-wise comparisons of customer requirements including odour (Od), taste (T), *colour* (C), other complaints (Ot) and ‘microbial safety’ (S). Each element a_{mn} of the upper triangle expresses the degree of importance of a ‘what’ m (e.g. taste) with respect to ‘what’ n (e.g. odour) (Khan & Sadiq 2005). The lower triangle of the matrix is the reciprocal of these comparisons.

$$A = \begin{array}{c|ccccc|} & \text{Od} & \text{T} & \text{C} & \text{Ot} & \text{S} \\ \text{Od} & 1 & 1 & 0.5 & 0.4 & 0.5 \\ \text{T} & 1 & 1 & 0.5 & 0.4 & 0.5 \\ \text{C} & 2 & 2 & 1 & 0.2 & 0.4 \\ \text{Ot} & 2.5 & 2.5 & 5 & 1 & 0.3 \\ \text{S} & 2 & 2 & 2.5 & 3.33 & 1 \end{array} \qquad (5)$$

To obtain preference weights (w_i) for each ‘what’, the geometric mean of each row of the matrix A is determined and then normalized with respect to the total sum of all the geometric means. The vector W of preferences (prioritized ‘whats’) for the judgment of each panel member is established. The arithmetic mean of these weights (around 10 persons were contacted) is computed to get each ‘what’ final preference weight (Equation (6)).

$$W = \begin{bmatrix} w_{\text{Odour}} \\ w_{\text{Colour}} \\ w_{\text{Tastes}} \\ w_{\text{Others}} \\ w_{\text{Microbial Safety}} \end{bmatrix} = \begin{bmatrix} 0.096 \\ 0.107 \\ 0.127 \\ 0.095 \\ 0.575 \end{bmatrix} \qquad (6)$$

This prioritizing of ‘what’ follows a similar trend to that observed by Kirmeyer *et al.* (2000) based on a large survey defining consumer drinking water priorities.

Prioritizing ‘hows’

Three different methods, namely (1) independent scoring, (2) Lyman’s and (3) Wasserman’s normalization, were implemented to prioritize ‘hows’. Lyman’s normalization aims to address the issues identified in the independent scoring method and Wasserman’s method is a generalization of Lyman’s method. To favour understanding, all three methods will be presented and applied and their results will be compared.

Independent scoring method

The *independent scoring method* is a classic QFD method that uses the relationship matrix between ‘whats’ and ‘hows’ (Table 2), and the preference weights of each ‘what’ (Equation (6)). Table 3 presents the weights of ‘hows’ obtained in terms of *absolute* and *relative* importance (last two lines of each part of Table 3, i.e. a, b and c). Table 3(a) shows weights for global data, where a relative weight higher than or equal to 10% is determined for three product characteristics (out of 12), namely: free residual chlorine, pipe breaks and turbidity. The combined impact of these ‘hows’ on ‘whats’ amounts to 49%. However, two other ‘hows’ – water age and water temperature – have a relative importance of ~9% each. These five technical characteristics contribute to 67% in satisfying customer needs.

During summer (Table 3(b)) free residual chlorine, pipe breaks, turbidity, water temperature and water age are again found to be the most important contributors. The relative importance obtained for each of these five ‘hows’ is at least 10%; their total contribution to meet customer requirements is 66%. For winter (Table 3(c)) the same technical characteristics contribute to 58% in meeting customer requirements. In comparison to summer, the impact of each of these five product characteristics slightly increases during winter except for free residual chlorine.

As mentioned earlier (see section “Methods for prioritizing ‘whats’ and ‘hows’, (i) independent scoring method”), the *independent scoring method* presents a major drawback in certain cases as it assigns a *weak* relative importance to some ‘hows’ that have a *strong* correlation with some ‘whats’ more important to the customer and vice versa. Normalization of the relationship matrix values serves to address these possible drawbacks.

Lyman’s normalization method

Lyman’s normalization method was repeated for all three types of data. In comparison with the *independent scoring method*,

Table 3 | Prioritizing product characteristics using the *independent scoring method* for drinking water in Quebec City

Customer requirements ('whats')	**Weights of 'whats' (d_i)**	**Product characteristics (or technical characteristics or design requirements) ('hows')** Water age	Pipe material	Pipe breaks	Pipe age	Free residual chlorine	Temperature	TTHMs	Turbidity	pH	Colour	UV_254	HPC
(a) Global data (four seasons combined)													
Odour	10%	1	1	9	1	1	1	1	1	1	1	1	1
Colour	11%	3	1	9	1	1	1	1	1	1	1	1	1
Taste	13%	1	1	3	3	1	1	1	3	1	3	3	1
Other (particles, turbidity)	9%	1	1	3	3	1	1	3	1	1	1	3	1
'Microbial safety'	58%	3	1	3	1	9	3	1	3	1	1	1	1
Weights of 'hows' (w_j) (absolute importance)		2.37[a]	1.00	4.22	1.44	5.60	2.15	1.19	2.40	1.00	1.25	1.44	1.00
Weights of 'hows' (w_j) (relative importance)		9%	4%	17%	6%	22%	9%	5%	10%	4%	5%	6%	4%
(b) Summer data													
Odour	10%	1	1	3	1	1	1	1	1	1	1	1	1
Color	11%	3	1	9	1	3	3	1	1	1	1	3	1
Taste	13%	3	1	1	3	1	1	1	3	1	3	3	1
Other (particles, turbidity)	9%	1	1	3	1	1	3	1	1	1	3	3	1
'Microbial safety'	58%	3	1	3	1	9	3	1	3	1	1	1	1
Weights of 'hows' (w_j) (absolute importance)		2.62	1.00	3.39	1.25	5.82	2.56	1.00	2.40	1.00	1.44	1.66	1.00
Weights of 'hows' (w_j) (relative importance)		10%	4%	13%	5%	23%	10%	4%	10%	4%	6%	7%	4%
(c) Winter data													
Odour	10%	1	1	1	1	1	1	1	1	1	1	3	1
Colour	11%	1	1	3	1	1	1	1	1	1	1	1	1
Taste	13%	1	1	3	1	1	1	1	1	1	1	1	1
Other (particles, turbidity)	9%	1	1	1	1	1	1	3	1	1	1	1	3
'Microbial safety'	58%	3	1	3	1	3	3	1	3	1	1	1	1
Weights of 'hows' (w_j) (absolute importance)		2.15	1.00	2.62	1.00	2.15	2.15	1.19	2.15	1.00	1.00	1.19	1.19
Weights of 'hows' (w_j) (relative importance)		11%	5%	14%	5%	11%	11%	6%	11%	5%	5%	6%	6%

[a] Example of weight calculation: w_j (j = Water age) = 2.37 = (10% × 1) + (11% × 3) + (13% × 1) + (9% × 1) + (58% × 3).

results obtained (not presented here in tabular form) are very similar. For global data, free residual chlorine, pipe breaks, turbidity, water age and water temperature remain the five most important product characteristics. Their total contribution to satisfy customer requirements decreases slightly from 67% to 65%. For summer, the level of importance calculated for these 'hows' is 64%, versus 66% in the first method. Finally for winter, there is virtually no difference between the two methods regarding the contribution (58%) of these five product characteristics; even their order of importance is identical.

From these results, we can conclude that the drawbacks identified in the *independent scoring method* do not significantly affect the results in this particular case. This is because all the technical characteristics considered are not divided into sub-characteristics. In addition, a correlation, though *weak*, exists between each customer requirement and each technical characteristic. However, both methods fail to incorporate the correlation that might exist between product characteristics (i.e. the roof of the HoQ). This fact may be very important in reducing the cost of improvement action on two strongly correlated technical requirements to satisfy customer requirements. In effect, improvement action on only one of these two correlated 'hows' is sufficient to give the same level of satisfaction to consumers that action on the two would give. To handle this situation an alternative method known as Wasserman's normalization was used.

Wasserman's normalization method

Wasserman's normalization involves correlations that might exist between technical characteristics. These correlations constitute the correlation matrix, or roof, of the HoQ. Pearson's correlation coefficient for each pair of 'hows' is determined, and later only absolute values (neglect negative and positive signs) are used in the analysis. Similar to the relationship matrix, these values are mapped, here on a scale [0, 1] where *weak* is 0.1, *medium* 0.3 and *strong* 0.9. Table 4 (see the roof of the HoQ) provides these correlations for global (Table 4(a)), summer (Table 4(b)) and winter (Table 4(c)) data.

Correlation between most of the product characteristics was generally *weak*; however, it was *strong* in specific cases. For example, there is a *strong* relationship between turbidity and colour; between turbidity and UV_254 nm; and between colour and UV_254 nm. The relationship between free residual chlorine and UV_254 nm was *strong* during winter and for global data, whereas it was *medium* during summer. There was also a *strong* correlation between free residual chlorine and TTHMs and between temperature and TTHMs for both winter and summer; these relationships were respectively *medium* and *weak* for global data. It also appears that only during winter the relationship between free residual chlorine and water temperature was *strong*, whereas it was *weak* and *medium* for global and summer data, respectively.

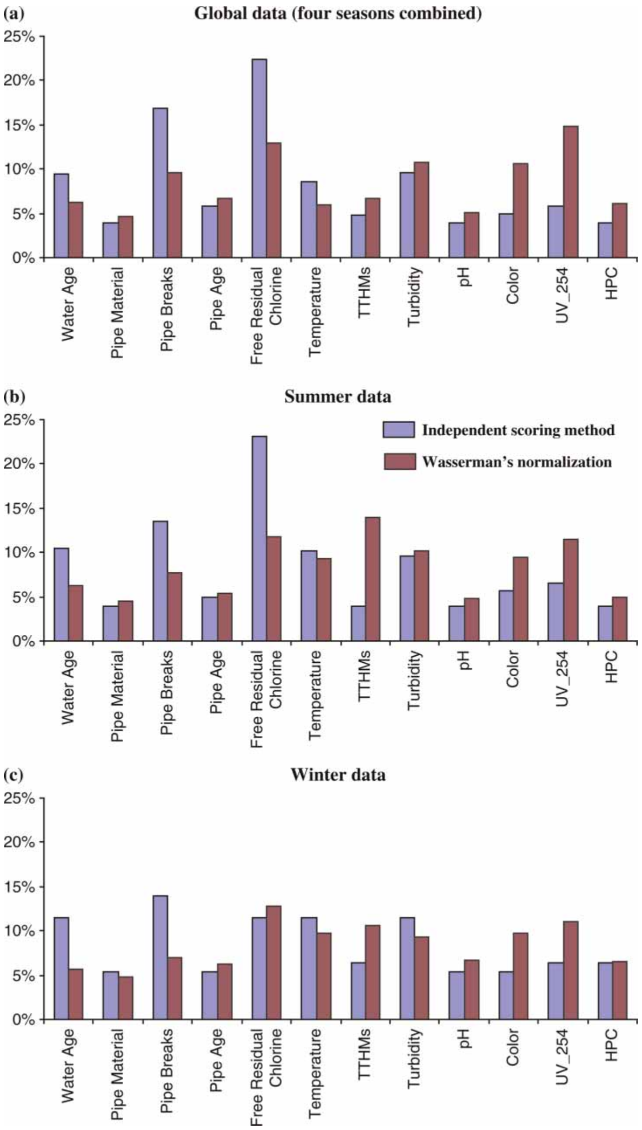


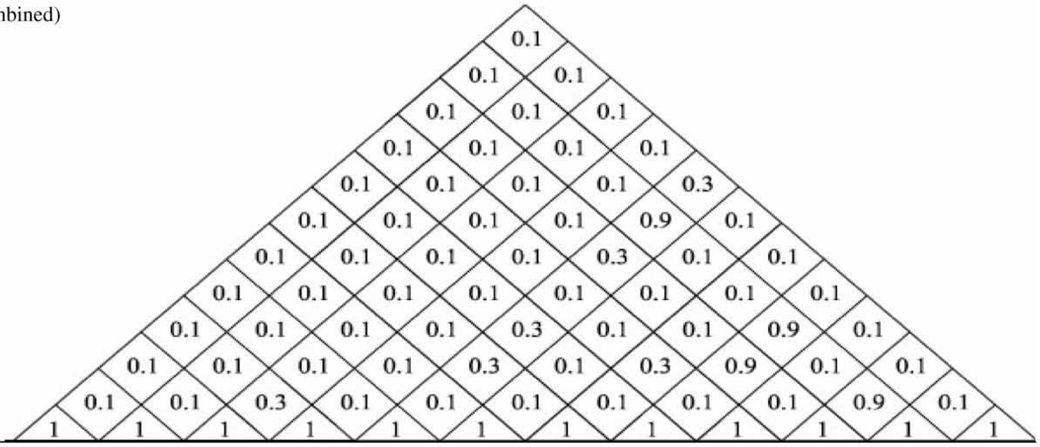
Figure 2 | Comparison of relative weights for product characteristics ('hows').

Figure 2 shows a comparison of the independent scoring and Wasserman's normalization methods. (Results for the independent scoring and Lyman's normalization methods are practically identical.) It can be observed that Wasserman's method has a significant effect on the prioritization of product characteristics. In effect, some 'hows' such as water colour, UV_254 nm (for three data sets) and TTHMs (for both summer and winter data) tend to have an increasing impact on the 'whats'. On the other hand, the impacts of water age, pipe breaks, free residual chlorine and water temperature decrease slightly.

Contrary to the other two methods, when using Wasserman's method (Table 4), the most important product characteristics differ depending on the type of data. This is probably due to the interdependency between 'hows' (roof of the HoQ of Table 4). For global data, UV_254 nm, free residual chlorine, turbidity, colour and pipe breaks are found to be the most important product characteristics. These parameters contribute to meet 60% of customer requirements. Their individual relative importance varies from 10 to 15%. The levels of importance of temperature and water age in particular decrease substantially from the

Table 4 | Prioritizing product characteristics using Wasserman's normalization method for drinking water in Quebec City

(a) Global data (four seasons combined)

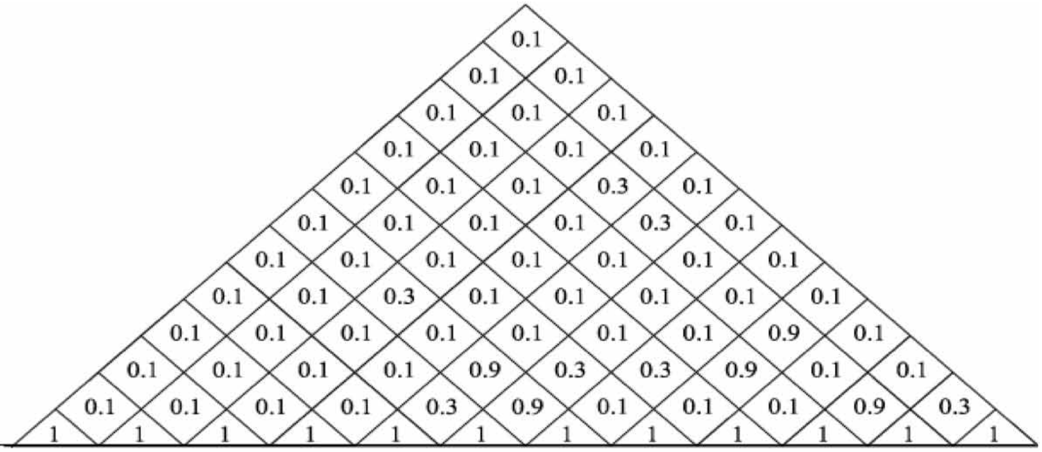


Customer requirements ('whats')	Weights of 'whats' (*di*)	Product characteristics (or technical characteristics or design requirements) ('hows')											
		Water Age	**Pipe Material**	**Pipe Breaks**	**Pipe Age**	**Free Residual Chlorine**	**Temp.**	**TTHMs**	**Turbidity**	**pH**	**Color**	**UV_254**	**HPC**
Odor	10%	0.06	0.06	0.20	0.09	0.09	0.06	0.06	0.09	0.06	0.09	0.10	0.06
Color	11%	0.09	0.05	0.19	0.09	0.08	0.05	0.06	0.09	0.06	0.09	0.10	0.06
Taste	13%	0.05	0.05	0.08	0.08	0.10	0.05	0.05	0.15	0.05	0.15	0.15	0.05
Other (particles turbidity)	9%	0.05	0.05	0.09	0.09	0.11	0.05	0.09	0.11	0.06	0.11	0.12	0.05
'Microbial safety'	58%	0.07	0.04	0.07	0.05	0.15	0.07	0.07	0.11	0.05	0.10	0.17	0.07
Weights of 'hows' (*wj*) (absolute importance)		0.06	0.05	0.10	0.07	0.13	0.06	0.07	0.11	0.05	0.11	0.15	0.06
Weights of 'hows' (*wj*) (relative importance)		6%	5%	10%	7%	13%	6%	7%	11%	5%	11%	15%	6%

(*continued*)

Table 4 | continued

(b) summer data



Customer requirements ('whats')	Weights of 'whats' (*di*)	Product characteristics (or technical characteristics or design requirements) ('hows')											
		Water Age	Pipe Material	Pipe Breaks	Pipe Age	Free Residual Chlorine	Temp.	TTHMs	Turbidity	pH	Color	UV_254	HPC
Odor	10%	0.06	0.06	0.11	0.06	0.09	0.09	0.12	0.10	0.06	0. 10	0.11	0.06
Color	11%	0.07	0.05	0.14	0.05	0.09	0.09	0.13	0.09	0.05	0.09	0.10	0.05
Taste	13%	0.07	0.05	0.05	0.08	0.07	0.07	0.07	0.14	0.05	0.14	0.16	0.05
Other (particles turbidity)	9%	0.05	0.05	0.08	0.06	0.08	0.09	0.11	0.13	0.05	0.13	0.13	0.06
'Microbial safety'	58%	0.06	0.04	0.07	0.05	0.15	0.10	0.16	0.09	0.05	0.08	0.11	0.05
Weights of 'hows' (*wj*) (absolute importance)		0.06	0.05	0.08	0.05	0.12	0.09	0.14	0.10	0.05	0.09	0.12	0.05
Weights of 'hows' (*wj*) (relative importance)		6%	5%	8%	5%	12%	9%	14%	10%	5%	9%	12%	5%

(*continued*)

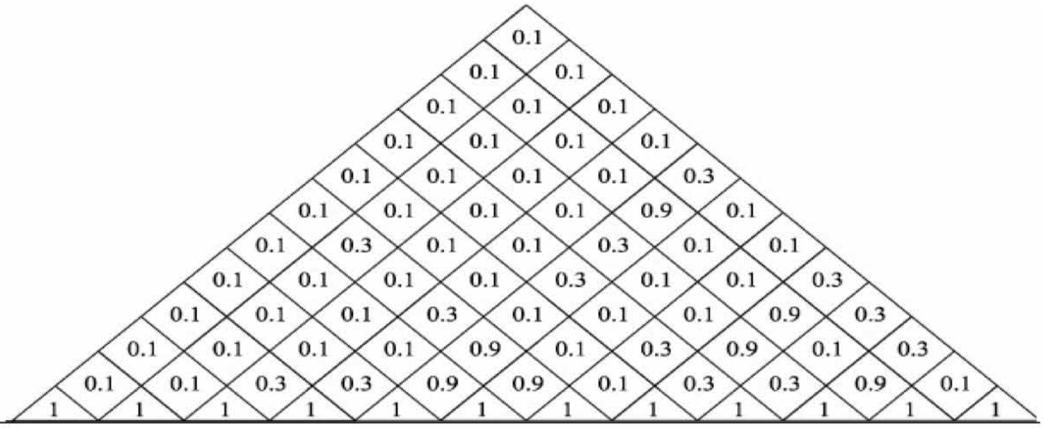
independent scoring method to Wasserman's method (Tables 3(a) and 4(a)).

During summer, four product characteristics (TTHMs, free residual chlorine, UV_254 nm and turbidity) have levels of importance higher than or equal to 10%. Their global impact on customer demands is approximately 48%, and when the product characteristic temperature is added to this list the global impact reaches 57%. Finally, for winter data, five technical characteristics, including free residual chlorine, UV_254 nm, TTHMs, water temperature and water colour make an individual contribution of at least 10% each. Their global contribution to satisfy customer demands is approximately 55%.

Table 4(a) (in the roof) shows that free residual chlorine and UV_254 nm together constitute redundant information (*strong* correlation, 0.9, between these two 'hows'); results are similar for turbidity and colour, turbidity and UV_254 nm and colour and UV_254 nm. In addition, Table 4(a) (see in the centre of the table the normalized relationship matrix, i.e. part 3 of the HoQ) shows that turbidity and colour have an equal impact on almost all the customer requirements; the same is true for turbidity and

Table 4 | continued

(c) Winter data



Customer requirements ('whats')	Weights of 'whats' (*di*)	Product characteristics (or technical characteristics or design requirements) ('hows')											
		Water Age	Pipe Material	Pipe Breaks	Pipe Age	Free Residual Chlorine	Temp.	TTHMs	turbidity	pH	Color	UV_254	HPC
Odor	10%	0.05	0.05	0.05	0.06	0.14	0.08	0.09	0.12	0.07	0.12	0.13	0.06
Color	11%	0.05	0.05	0.09	0.07	0.12	0.08	0.10	0.09	0.07	0.10	0.10	0.07
Taste	13%	0.05	0.0.5	0.09	0.07	0.12	0.08	0.10	0.09	0.07	0.10	0.10	0.07
Other (particles turbidity)	9%	0.04	0.06	0.05	0.06	0.14	0.10	0.12	0.09	0.08	0.09	0.09	0.09
'Microbial safety'	58%	0.06	0.04	0.07	0 06	0.13	0.11	0.11	0.09	0.06	0.10	0.11	0.06
Weights of 'hows' (*wj*) (absolute importance)		0.06	0.05	0.07	0.06	0.13	0.10	0.11	0.09	0.07	0.10	0.11	0.07
Weights of 'hows' (*wj*) (relative importance)		**6%**	5%	7%	6%	13%	10%	11%	9%	7%	10%	11%	7%

UV_254 nm. Therefore, it may be advisable to include/improve only turbidity to satisfy all parts of the 'whats' related to these three 'hows'. A quasi-similar situation (i.e. redundant information and equal impact on all the customer requirements) is observed for turbidity and colour again for both summer (Table 4(b)) and winter (Table 4(c)) and for colour and UV_254 nm during winter (Table 4(c)).

These results suggest that, out of three technical characteristics, it may be sufficient to consider only one, say turbidity, to satisfy customer needs. Introducing/improving a single attribute rather than three to provide the same level of satisfaction (that improving the three would provide) to the consumers would allow a better management of available resources (financial and human).

SENSITIVITY ANALYSIS

To test the application robustness, a comprehensive sensitivity analysis was carried out. Sensitivity analysis is a process of estimating the degree to which the output (the degree of importance of product characteristics) of a model changes as values of input factors change (the values of 'hows', not their importance; e.g. levels of free residual chlorine or turbidity, and/or the weight of 'whats'). This can be useful to quantify the change in output caused by uncertainty and variability in the values of input factors. Various methods of sensitivity analysis exist, for example the scatter plot, partial and rank correlation coefficients, multivariate regression, contributions to variance and probabilistic sensitivity analysis (Cullen & Frey 1999).

Three scenarios were studied to conduct the sensitivity analysis in this study:

- *Scenario 1 – values for the 'hows' are randomly generated*: For this purpose, a uniformly distributed probability density function for each technical characteristic is assumed. Then, within each zone (corresponding to at least one monitoring location) and for each 'how', a random number is generated. This random number (cumulative probability) is transformed into a real value (x) using the *minimum* ($x_{\min}$) and *maximum* ($x_{\max}$) values assumed for that specific technical characteristic:

$$x_r = x_{\min} + p_r \times (x_{\max} - x_{\min}) \tag{7}$$

  where x_r is the r-th random value of the 'how', $x_{\min}$ and $x_{\max}$ are respectively its minimum and maximum values and p_r is the r-th cumulative probability generated.

  The correlations between the values of 'whats' and these new values of 'hows' are computed and are used to build the relationship matrix described earlier.
- *Scenario 2 – customer has no preference, i.e. equal weights for each customer demand*: In this scenario, the relationship matrix does not change, but the importance of the technical characteristics changes.
- *Scenario 3 – values for the 'hows' are randomly generated and the 'whats' receive equal weights*: This is a combination of the two earlier scenarios.

Based on these scenarios, a new prioritization for technical characteristics was carried out. For brevity, only Wasserman's normalization method is discussed here for all three data sets (global, summer and winter data). The correlation coefficients between the 'hows' obtained previously (roof of Table 4) are used for the correlation matrix (roof of the HoQ). Results for each scenario for global data only are presented in Table 5 (HoQ shown without roof). Figure 3 shows a comparison of these results with results obtained using real values of 'hows'.

Scenario 1

Figure 3(a) shows that the pattern of the original results is maintained. Technical characteristics that have greater impact on customer requirements are virtually the same, except for pipe breaks. The impact of pipe breaks on 'whats' decreases slightly contrary to the four other most important 'hows'. The latter, i.e. UV_254 nm, free residual chlorine, turbidity and colour, have individual impact greater than 11%. Their total impact on customer needs is approximately 54%.

Scenario 2

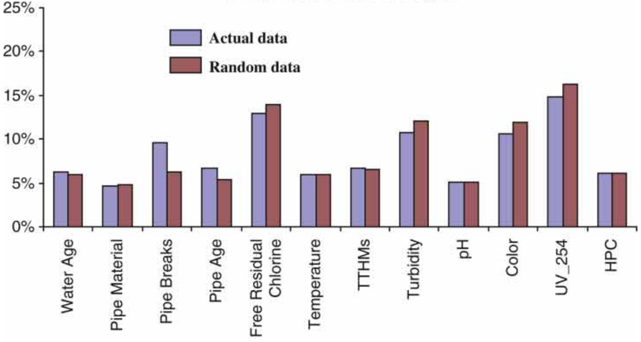
Figure 3(b) shows that when 'whats' carry equal weights, the five most important 'hows', i.e. UV_254 nm, free residual chlorine, turbidity, colour and pipe breaks remain unchanged. But, their global contribution to meet customer requirements is 56% instead of 60%. The relative importance of UV_254 nm decreases slightly, likewise for free residual chlorine, whereas the relative importance of pipe breaks increases slightly. Turbidity and colour record practically no change in their relative importance.

The order of importance changes as follows: UV_254 nm obtains the first rank (as for actual data), pipe breaks the second, while free residual chlorine, turbidity and colour obtain the third rank due to their identical level of importance. It can be noted that free residual chlorine was ranked second for actual data (data described in the section related to the application of QFD). These changes may be explained by the strength of the relationships between 'whats' and 'hows' (Table 2(a)). Indeed, if a technical characteristic has a *strong* relationship with a customer requirement, its impact on customer needs decreases when the weight of the 'what' decreases. Similarly, the impact of the 'how' increases when the weight of the 'what' increases (if their relationship is *strong*). These two situations are illustrated clearly, e.g. in the first case by free residual chlorine ('how') and 'microbial safety' ('what': decrease from 58 to 20%) and in the second by pipe breaks ('how') and two 'whats' (odour: increase from 10 to 20% and *colour*: from 11 to 20%).

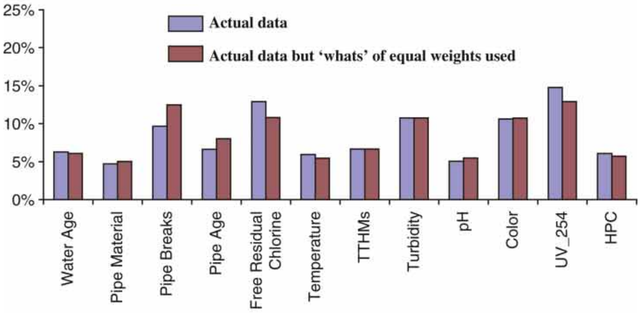
Table 5 | Prioritizing product characteristics using Wasserman's normalization method for three different scenarios

		Product characteristics (or technical characteristics or design requirements) ('hows')											
Customer requirements ('whats')	**Weights of 'whats' (d_i)**	**Water age**	**Pipe material**	**Pipe breaks**	**Pipe age**	**Free residual chlorine**	**Temperature**	**TTHMs**	**Turbidity**	**pH**	**Colour**	**UV_254**	**HPC**
(a) Global data (four seasons combined) ***Scenario 1 ('whats' have different weights, 'hows' have random values)***													
Odour	10%	0.06	0.06	0.07	0.07	0.11	0.06	0.07	0.11	0.07	0.11	0.13	0.07
Colour	11%	0.06	0.06	0.07	0.07	0.11	0.06	0.07	0.11	0.07	0.11	0.13	0.07
Tastes	13%	0.04	0.04	0.04	0.04	0.14	0.04	0.04	0.17	0.04	0.17	0.19	0.04
Others (particles, turbidity)	9%	0.05	0.05	0.05	0.05	0.12	0.05	0.06	0.15	0.05	0.15	0.16	0.05
'Microbial safety'	58%	0.07	0.04	0.07	0.05	0.15	0.07	0.07	0.11	0.05	0.10	0.17	0.07
Weights of 'hows' (w_j) (absolute importance)		0.06	0.05	0.06	0.05	0.14	0.06	0.06	0.12	0.05	0.12	0.16	0.06
Weights of 'hows' (w_j) (relative importance)		6%	5%	6%	5%	14%	6%	6%	12%	5%	12%	16%	6%
(b) Global data (four seasons combined) ***Scenario 2 ('whats' have equal weights (20%), actual (real measured) data of 'hows' are used)***													
Odor	20%	0.06	0.06	0.20	0.09	0.09	0.06	0.06	0.09	0.06	0.09	0.10	0.06
Color	20%	0.09	0.05	0.19	0.09	0.08	0.05	0.06	0.09	0.06	0.09	0.10	0.06
Tastes	20%	0.05	0.05	0.08	0.08	0.10	0.05	0.05	0.15	0.05	0.15	0.15	0.05
Others (particles, turbidity)	20%	0.05	0.05	0.09	0.09	0.11	0.05	0.09	0.11	0.06	0.11	0.12	0.05
'Microbial safety'	20%	0.07	0.04	0.07	0.05	0.15	0.07	0.07	0.11	0.05	0.10	0.17	0.07
Weights of 'hows' (w_j) (absolute importance)		0.06	0.05	0.12	0.08	0.11	0.05	0.07	0.11	0.05	0.11	0.13	0.06
Weights of 'hows' (w_j) (relative importance)		6%	5%	12%	8%	11%	5%	7%	11%	5%	11%	13%	6%
(c) Global data (four seasons combined) ***Scenario3 ('whats' have equal weights (20%), 'hows' have random values)***													
Odour	20%	0.06	0.06	0.07	0.07	0.11	0.06	0.07	0.11	0.07	0.11	0.13	0.07
Colour	20%	0.06	0.06	0.07	0.07	0.11	0.06	0.07	0.11	0.07	0.11	0.13	0.07
Taste	20%	0.04	0.04	0.04	0.04	0.14	0.04	0.04	0.17	0.04	0.17	0.19	0.04
Others (particles, turbidity)	20%	0.05	0.05	0.05	0.05	0.12	0.05	0.06	0.15	0.05	0.15	0.16	0.05
'Microbial safety'	20%	0.07	0.04	0.07	0.05	0.15	0.07	0.07	0.11	0.05	0.10	0.17	0.07
Weights of 'hows' (w_j) (absolute importance)		0.06	0.05	0.06	0.06	0.13	0.06	0.06	0.13	0.06	0.13	0.16	0.06
Weights of 'hows' (w_j) (relative importance)		6%	5%	6%	6%	13%	6%	6%	13%	6%	13%	16%	6%

(a) *Scenario 1*: values for the 'hows' are randomly generated, 'whats' have different weights



(b) *Scenario 2*: 'whats' have equal weights (20%)



(c) *Scenario 3*: values for the 'hows' are randomly generated, 'whats' have equal weights (20%)

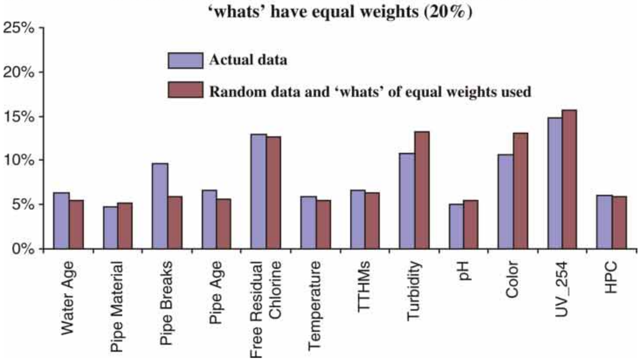


Figure 3 | Comparison of relative weights for product characteristics ('hows') in Wasserman's normalization using actual data, random data and 'whats' of equal weights.

Scenario 3

Finally, when equal weights are assigned to 'whats' and values of 'hows' are randomly generated, results (Figure 3(c)) are similar to those obtained using the actual data. UV_254 nm, turbidity, colour, free residual chlorine and to a lesser extent pipe breaks remain the most important product characteristics. The impacts of the first three on the 'whats' increase slightly; the impact of free residual chlorine decreases slightly, whereas the impact of pipe breaks is reduced in half. The individual impacts of UV_254 nm, free residual chlorine, turbidity and colour exceed 12%, whereas it is 6% for pipe breaks. The global impact of these technical characteristics on customer needs is 61%, against 60% for actual data.

As in Scenario 2, the strength of the relationships between 'whats' and 'hows' may explain the slight changes in the relative importance of some 'hows'. Indeed, the relationship between free residual chlorine ('how') and 'microbial safety' ('what') is *strong* (i.e. 9). Thus, when the relative weight of this 'what' decreases (from 58% to 20%), the relative importance of free residual chlorine also decreases. The impact of pipe breaks on customer needs is also reduced because this 'how' has a *medium* relationship with 'microbial safety' for which the weight decreases from 58 to 20%. The relationship between pipe breaks ('how') and the other four customer requirements is *weak*. The increase in the weight of these 'whats' (i.e. odour, *colour*, taste and 'other') probably limits the decrease of the impact of this 'how'.

The impact of UV_254 nm (a 'how') increases because it has a *strong* relationship with taste (a 'what') for which the relative weight increases from 13 to 20%. UV_254 nm also has a *medium* correlation with the customer need 'other', whose relative weight increases from 9 to 20%. The relative importance of turbidity increases from 11 to 13% because this 'how' has a *medium* relationship with the 'whats' 'other' and taste, for which the weights increase from 9 to 20% and 13 to 20%, respectively. The increased weight of taste ('what' that has a *medium* relationship with colour, a 'how') would explain the impact increase of colour on customer needs.

DISCUSSION

To identify the most important technical characteristics, four different cases are considered that include actual data, Scenario 1, Scenario 2 and Scenario 3. In each case, the global data, summer data and winter data are considered. Consequently 12 ranking orders are established for technical characteristics. Table 6 shows that 4 out of

Table 6 | Ranking product or technical characteristics ('hows') after prioritizations based on Wasserman's normalization method

	Type of prioritization		Water age	Pipe material	Pipe breaks	Pipe age	Free residual chlorine	Temperature	TTHMs	Turbidity	pH	Colour	UV_254	HPC
Global data	Actual data *(Wasserman's method)*		8	12	5	7	2	10	6	3	11	4	1	9
	Sensitivity analysis	*Scenario 1*	8	12	6	10	2	9	5	3	11	4	1	7
		Scenario 2	8	12	2	6	3	11	7	4	10	5	1	9
		Scenario 3	9	12	6	8	4	10	5	2	11	3	1	7
	Rank		**9**	**12**	**5**	**7**	**2**	**10**	**6**	**3**	**11**	**4**	**1**	**8**
Summer data	Actual data *(Wasserman's method)*		8	12	7	9	2	6	1	4	11	5	3	10
	Sensitivity analysis	*Scenario 1*	8	12	7	9	5	6	2	3	11	4	1	10
		Scenario 2	8	12	7	10	2	4	1	5	9	6	3	11
		Scenario 3	9	12	7	10	3	5	1	4	8	6	2	11
	Rank		**8**	**12**	**7**	**9**	**3**	**5**	**1**	**4**	**10**	**5**	**2**	**11**
Winter data	Actual data *(Wasserman's method)*		11	12	7	10	1	5	3	6	8	4	2	9
	Sensitivity analysis	*Scenario 1*	11	12	9	10	1	6	3	5	7	4	2	8
		Scenario 2	12	11	7	10	1	6	3	5	8	4	2	9
		Scenario 3	11	12	10	9	1	7	5	4	6	3	2	8
	Rank		**11**	**12**	**8**	**10**	**1**	**6**	**3**	**5**	**7**	**4**	**2**	**9**
	Final Rank		**9**	**12**	**6**	**8**	**2**	**7**	**3**	**4**	**9**	**5**	**1**	**9**

12 distributed drinking water characteristics are most important to satisfy customer needs:

- *Global data:* the most important technical characteristics in descending order are UV_254 nm, free residual chlorine, turbidity and colour;
- *Summer data:* the most important technical characteristics in descending order are TTHMs, UV_254 nm, free residual chlorine and turbidity;
- *Winter data:* the most important product characteristics in descending order are free residual chlorine, UV_254 nm, TTHMs, colour and turbidity.

Based on 12 ranking orders, overall UV_254 nm is ranked first followed by free residual chlorine, TTHMs and turbidity. However, turbidity and UV_254 nm provide some redundant information (a *strong* correlation exists between these two 'hows' as given in Table 4), and they have practically the same impact on almost all customer needs. Therefore, to eliminate this redundancy and reduce cost, only turbidity (not UV_254 nm) is used in the list of technical requirements to meet customer needs. (Turbidity is a parameter very well known by researchers, can be improved more easily than UV_254 nm by utilities. Its measurement is easy and does not require, as for UV_254 nm, a quartz cell, which is expensive and fragile.)

To satisfy customer needs, these analyses demonstrated that the utility manager has to focus on (i) maintaining sufficient levels of free residual chlorine for ensuring microbiological stability in the DN, but just enough to avoid consumer complaints (which is why it is the biggest challenge). As stated previously in the penultimate paragraph of the introduction, based on Proulx *et al.* (2010) study about the public perception of excess of chlorine, studied utility managers should try to maintain a level of free residual chlorine between 0.3 and 0.4 mg/L; (ii) removing both turbidity and TTHMs levels to the maximum. In addition to the three technical characteristics (free residual chlorine, TTHMs and turbidity) identified earlier, in summer, temperature seems to play an important role and special attention must be given to water colour, whereas in winter only water colour requires particular attention.

CONCLUSIONS

In this study, the use of the QFD approach is demonstrated for the first time in the management of drinking water quality in water distribution networks. Principal customer expectations ('whats') were essentially the complaints recorded by the utility during six years, except for 'microbial safety', an attribute defined by an expert panel. Twelve parameters were considered and documented as product or technical characteristics ('hows'), which must be prioritized to meet the customer requirements. These technical attributes were classified as water quality parameters (related to the distributed water), and DN parameters (related to structural integrity and hydraulic characteristics of the network). The following techniques and tools were used to implement the proposed approach: (i) GIS to determine an area of influence (zone) for all monitoring locations and document all customer requirements and technical characteristics in each of the 52 zones, (ii) AHP for prioritizing customer requirements and (iii) the QFD approach for translating customer needs into adequate water utility requirements.

The results showed that the most dominant product or technical characteristics (highest impact on customer requirements) include UV_254 nm, free residual chlorine, TTHMs, turbidity and colour. Some minor changes in their ranks were observed for different data sets (i.e. global, summer, winter). Out of 12, the top 5 'hows' (usually the same) contribute to satisfy at least 54% of customer needs: for winter (54% whatever the scenario), for summer (59, 55 and 59% for Scenarios 1, 2 and 3, respectively), for global data (60, 59 and 61% for Scenarios 1, 2 and 3, respectively) and for actual data (55, 57 and 60% for winter, summer and global data, respectively). Redundancy was also observed between some 'hows', such as turbidity and UV_254 nm, turbidity and colour and colour and UV_254 nm. This suggests that it may be sufficient to use/improve only turbidity (instead of the three parameters) to satisfy customer needs and reduce the cost of monitoring and taking actions based on many redundant parameters.

A sensitivity analysis showed that the application of the QFD approach is very robust. It is recommended that utility managers in drinking water management give special attention to three product characteristics, i.e. free residual chlorine, turbidity and TTHMs (UV_254 nm being redundant with turbidity), to satisfy customer requirements effectively and reconcile the 'actual' risk (offered quality) with 'perceived' risk (quality perceived by the consumer).

To apply the approach, utility managers must collect complaints data on distributed drinking water, monitoring data as stated by regulations and guidelines, for at least one year, and all hydraulics and structural data related to the distribution network. To improve further the proposed QFD approach, several extensions are recommended for future studies: (i) increase the number of product characteristics ('hows') on conditions if they are not strongly correlated, (ii) integrate QFD with fuzzy set theory (Ross 2004) to deal with uncertainty and human subjectivity and (iii) introduce Part 4 of the HoQ in analysis to allow a *competitive benchmarking assessment* for the distributed drinking water with respect to alternative water (e.g. bottled water). Obviously regular communication between a utility and its customers is vital. It will serve to modify progressively and effectively adjust actions directed to all three dimensions of quality in such a way that distributed drinking water quality (offered quality, Q_o) approaches both perceived quality (Q_p) and expected quality (Q_a). This will help mitigate recourse to the increased use of alternatives to municipal tap water.

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