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WATER DISTRIBUTION SYSTEMS: EFFECT OF GEOGRAPHICAL LOCATION ON EXPERT JUDGEMENT

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Abstract: Water distribution systems are one of the key elements in the underground infrastructure network. There are large numbers of studies on the various aspects of deterioration, failure, rehabilitation and replacement of water pipelines in which certain factors, along with their weights of importance, are assumed to influence the performance of water distribution pipelines. These weights of importance are mostly calculated based on expert judgement which is shaped by years of experience and the demographic distribution of experts. Since these factors will be used in the performance prediction of the pipelines, the accuracy of these models will be highly dependent on the experts' opinions. This study aims to evaluate the impact of location on expert judgement in performance assessment of water distribution networks. Two groups of professionals with the same set of circumstances from Canada and Qatar have been chosen to determine the influence of location on decision-making. The same set of questionnaires was sent to both groups asking them to identify the most important factors in the deterioration of water pipelines and their respective weights of importance. Results show that the experts' opinions are greatly colored by their location and the surrounding environment, which highlights the importance of considering these factors in further studies.

1 INTRODUCTION

The water distribution network (WDN) represents the majority of assets of a water supply system. It is a sophisticated assembly of hydraulic elements necessary to deliver potable water to human consumers. Water is a vital natural supply for mankind's survival, and it is indispensable to several industrial processes—such as food processing and cooling. The WDN is reported as being the most expensive part of water supply systems (Giustolisi, Laucelli & Savic. 2006), and it is usually owned and operated by public entities, such as municipalities. The experts in charge of their design are civil engineers and asset managers (Srdjevic & Medeiros. 2008). There are several approaches for management and modeling the WDN that can be classified as either old-style or modern methods. Methods that utilize linear and nonlinear optimization schemes are classified as the former, while modern practices are those that employ heuristic optimization techniques, such as genetic algorithms.

The recent 2016 Canadian Infrastructure Report Card for drinking water indicates that 29% of the drinking water systems of Canada are rated from fair to very poor, and the replacement cost of these assets is estimated to be $24.5 billion Canadian dollars. There are over 5,400 kilometers of water mains in Qatar experiencing a high rate of water leakage in various parts of the country. The leakage is estimated at 35% in Doha and at 30% in the rest of the area (Global Water Index. 2010). There are several factors that should be considered along with their respective weights of importance when planning and modeling a WDN, such as location, future and current demand, leakage, pipe size and material and water quality. In this paper, the weights of importance of the deterioration factors are calculated and compared based on two series of expert judgements from the two distinctive locations, Qatar and Canada, and the effect of location on the experts' decision-making is identified. It is assumed that the geographical location where the experts work and have gained their experience has a significant effect on their judgement. This research utilizes the integration of the fuzzy analytic hierarchy process (FAHP) and Shannon entropy to determine the weights of importance of each factor for the two sets of questionnaires. Knowing the impact of location, it is possible to generalize the results from one location to another in order to benefit from one model which has been developed for a specific WDN.

2 PREVIOUS PRACTICES IN WATER SYSTEMS

The FAHP method is mainly used to solve hierarchical and multi-criteria decision-making problems. AHP assigns relative weights to variables by analyzing the judgments of individual experts and transferring them to a hierarchical structure. This structure demonstrates associations among objectives, parameters and sub-parameters. It could be said that the ultimate goal of the analytic hierarchy process (AHP) is collecting the experts' judgments. Several studies have investigated the behaviour of water segments utilizing this method. A hierarchical Bayesian-based failure model was proposed by Watson et al. (2004) to predict failure rate from different data sources, such as engineering knowledge and historical failure data. Two different pipe samples were used in the validation process. Once the break rates were illustrated versus time in both predicted models and the observed data, it can be seen that the Bayesian model predicts better results than normal estimation until the pipe reaches the age of 25 years. After that, the results from both models are similar. Al-Barqawi and Zayed (2006) used AHP to assess the water main's condition. The important factors were first identified, pair-wise comparisons were performed and condition assessment records were calculated. Al-Barqawi and Zayed (2008) also presented an integrated AHP/artificial neural network (ANN) model to evaluate the performance of water mains. AHP was used to calculate the weights of importance and the condition of the pipelines. Zhou et al. (2009) developed an FAHP pipe condition assessment model which generates a pipe condition rating from fuzzy first-level and second-level condition indicators and validates the model using eight pipe samples. Physical indicators, load, external corrosion and historical breakage were the parameters used for first-level condition indicators. Pipe specifications, such as diameter, age, length, depth, water pressure, impact strength and maximum pressure, are the data requirements for second-level condition indicators. Later, Fares and Zayed (2010) established a hierarchical fuzzy expert system to estimate the risk of failure in water mains which ranges from 0 (least risk) to 10 (highest risk). Since AHP is not able to consider uncertainty in inputs and has other limitations, such as subjectivity, FAHP was introduced. It solved the problem of uncertainty by asking the respondents to enter all possible outcomes of the model in the pairwise comparison matrix. It means that the lowest and highest possible values are entered in regular AHP, which renders the FAHP difficult and time-consuming (Fares, 2008). Although fuzzy logic has covered the limitations of the AHP, the heuristic models still entail inconsistency in expert judgments. Since the experience varies from individual to individual, the judgments are different. To solve the limitation of subjectivity in AHP, Shannon entropy is used. FAHP identifies the subjective weights from experts' judgements while the objective weights are calculated through Shannon entropy (Mavi, Goh & Mavi. 2016). Claude Shannon (1984) proposed a mathematical theory to measure the amount of information content of an information source. In this theory, the term entropy refers to the portion of information content that indicates the uncertainty of both the information source and the random variable, and defines how much information is earned when result i is observed. When the raw data of the decision-making matrix are identified completely, the entropy method could be used to evaluate the weights. There is more chance of occurrence for each value of i when entropy is higher (Shannon, 2001). Measuring uncertainty of a random variable i means that, when $E_i=0$, i would be a certain variable, not a random one. The concept of Shannon entropy refers to an accepted measure of uncertainty and fuzziness. This is the main reason for choosing this method for calculating the weights. Entropy recently has been used in reliability assessment studies in WDNs (Prasad & Tanyimboh. 2008, Shibu & Reddy. 2012, Tanyimboh, Tietavainen & Saleh. 2011) and was used in conjunction with AHP in weight determining in Zheng and Tian's (2009) study. Furthermore, Zou et al. (2006) assessed water quality through the integration of FAHP and entropy, and the results were favourable.

3 RESEARCH METHHODODLOGY

The overall flow of the research process will be described here. In the data collection phase, the questionnaire is designed, distributed and collected. After that, the collected responses are analyzed for both FAHP and Shannon entropy methods. In FAHP, the matrix of pairwise comparison is built and checked to determine whether the responses are consistent or not. Afterwards, the data are analyzed and weights of importance are calculated. After probability calculation and normalization in Shannon entropy, the entropy and degree of diversification are computed for each factor, and the weights of importance are estimated. Finally, the weights of importance of factors affecting pipeline deterioration through the integration of FAHP and entropy are calculated. These steps are performed for both groups of experts in the two locations, and the results are compared to identify the effect of location on expert judgement.

4 DATA COLLECTION PROCEDURE

The survey was conducted in September 2016. The online questionnaire was designed using the Qualtrics (Provo, UT, USA) data collection website. To choose the experts, the authors first examined their personal networks and selected as many names as possible that fit. Since the personal contacts of the authors are limited and biased, different municipalities were contacted and asked to recommend experts who had a deep understanding of WDNs and pipeline deterioration. Afterwards, the experts received a “qualification checklist” and declared their expertise. Those experts who did not have enough knowledge were politely excused. The required expertise was divided into three categories: piping, water and maintenance. The piping category consisted of piping engineers and water pipeline experts. Water consultants and water infrastructure engineers were classified under the water category. Leak detection specialists, operation and maintenance (O&M) engineers and maintenance supervisors in infrastructure were classified under the maintenance category. A total of 13 experts from Qatar and 11 experts from Canada were chosen. Canada was chosen as one of the locations for experts since it is famous for its harsh winter weather, with temperatures sometimes reaching –40 °C. The average summer temperature is 25 °C, and the average annual rainfall is 1,000 mm. On the other hand, Qatar was chosen as the other location since the temperature can surpass the 45 °C by noon in the summer. The average winter temperature is approximately 24 °C, and the average annual rainfall is less than 75 mm. A total of 24 questionnaires were collected from experts to determine the weight of importance of each factor in water pipeline deterioration. The years of experience and the area of expertise of the respondents in Qatar and Canada are summarized in Figure 1 and 2, respectively.

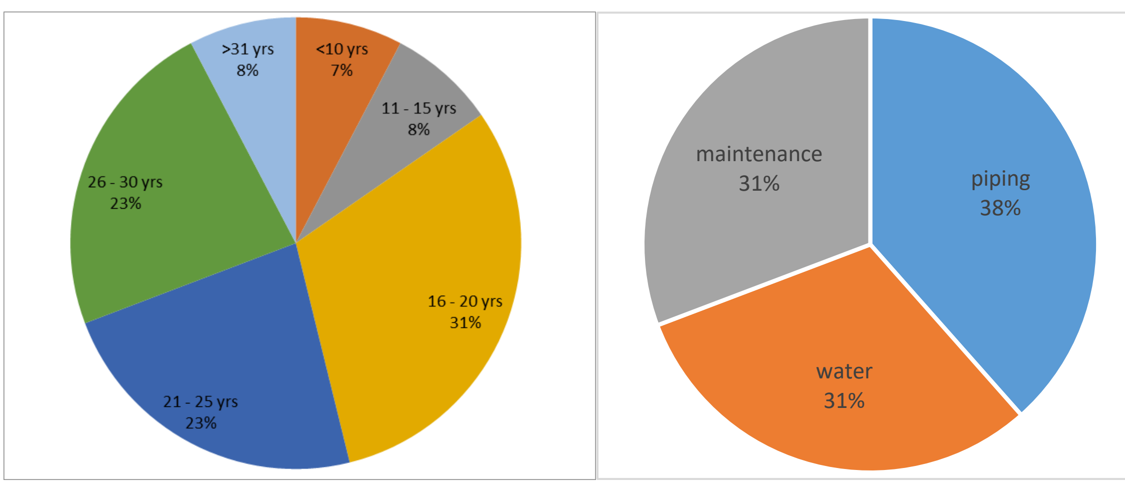

Figure 1. Years of experience and area of expertise of participants from Qatar

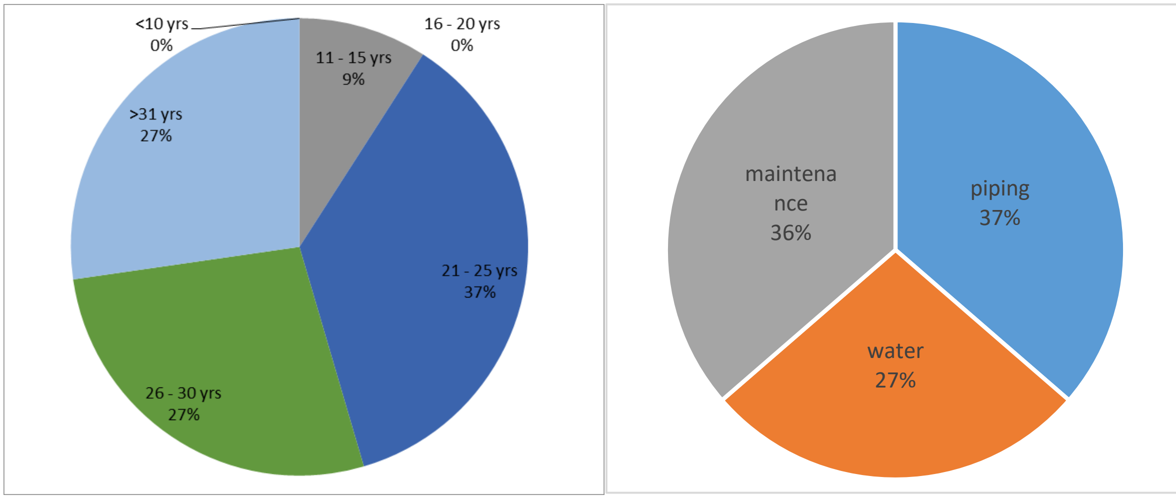

Figure 2. Years of experience and area of expertise of participants from Canada

In the six-question questionnaire, the experts were asked to identify the relative importance of each criterion in pipeline deterioration, both separately and in respect to others. The recommended factors were classified as physical, environmental and operational factors, and a total of 16 were then sorted into these three classes with seven, five and four factors, respectively. The structure of the questionnaire consists of four parts: informed consent form, respondent's information, brief description of parameters and questions. In Questions 1 to 4, the respondents are asked to rank the factors in the physical, environmental and operational classes based on their relative importance from "extremely low importance" to "extremely high importance." Question 5 seeks to determine the weight of importance through entropy by asking respondents to prioritize factors based on their importance. Experts were asked to challenge the questions and suggested factors in Question 5 if there were any concerns.

4.1 Pairwise comparison matrix

The primary step is building the matrix for pairwise comparison and checking its consistency. After that, the relative weights of parameters and sub-parameters were determined (Vahidnia, Alesheikh, Alimohammadi & Bassiri. 2008).

$$A = \begin{vmatrix} 1 & W_{12} & \dots & W_{1n} \\ W_{21} & 1 & \dots & W_{2n} \\ \vdots & \vdots & 1 & \vdots \\ W_{n1} & W_{n2} & \dots & 1 \end{vmatrix}$$

In this matrix, W_{12} is the weight of parameter 1 in respect to parameter 2. All the arrays in matrix A are fuzzy triangular numbers (l_{ij}, m_{ij}, u_{ij}). To analyze FAHP, Larhorn and Pedric (1983) suggested a method based on minimum logarithmic squares. Due to its complexity and ambiguity, this method was not well received (Nepal, Yadav, & Murat. 2010). Later, Chang (1996) proposed the extent analysis method (EAM) that used fuzzy triangular numbers and became more common in FAHP calculations (Nepal, Yadav & Murat. 2010). It is this method that is used in this study. In this method, the triangular number of S_k is calculated for each row of the pairwise comparison matrix from below, in which *k* is the row number, *i* is the alternative and *j* is the criterion:

[4] $S_k = \sum_{j=1}^{n} M_{kj} \times \left[\sum_{i=1}^{m} \sum_{j=1}^{n} M_{ij}\right]^{-1}$.

Computing S_k, its magnitude should be determined in respect to others, and the result should be normalized from the following equation:

[5] $W_i = \frac{w_i'}{\sum w_i'}$.

After finding acceptable results, the priority matrices are combined by multiplying the weight of factors (W_i) and the weight of sub-factors (Y_i), to calculate the overall score. Subsequently, the consistency index (CI), which is the degree of deviation from consistency, is checked. Afterward, the consistency ratio (CR), defined as the ratio of the CI divided by the random inconsistency index (RI) for random comparisons, is calculated:

[6] $CR = \frac{CI}{RI}$

The built pairwise comparison matrix for FAHP was again used to perform the Shannon entropy method. Normalizations were performed first, and entropy was calculated afterward. Then, the degree of diversification and weight of importance were computed from calculated entropy:

[7] $\overline{W_{ji}} = \frac{W_{ji}}{\sum_{j=1}^{n} W_{ji}}\ j = 1,\dots,n; i = 1,\dots,n$.

The entropy E_i is computed through the following equations, where E_0 is the entropy constant and is $\frac{1}{\ln(n)}$:

[8] $E_i = -E_0 \sum_{j=1}^{n} \overline{W_{ji}}\, ln\, \overline{W_{ji}}\ \ i = 1,\dots,n$,

[9] $d_i = 1 - E_i$ and

[10] $w_i = \frac{d_i}{\sum_{i=1}^{n} d_i}, i = 1,\dots,n.$

After finding the weights of importance from FAHP (w_j), they can be combined with the computed degree of importance from entropy (y_j) using the following equation:

[11] $W_j = \frac{y_j w_j}{\sum_{j=1}^{n} y_j w_j} \quad \forall j.$

5 RESULTS AND DISCUSSION

The collected responses were analysed and total weights of importance for the parameters identified through FAHP in each expert group are summarized in Table 1. As can be seen, all the experts believed that physical factors have the highest effect in deterioration of the water pipelines. In the opinion of the Canadian experts, operational and environmental factors are ranked as the second and third most important categories in pipeline deterioration. The Qatari experts believed that environmental factors are more important than operational factors. In the category of physical factors, pipe material, pipe installation and pipe age are the first three most significant factors in deterioration, according to the responses of both the Canadian and Qatari experts. In the category of environmental factors, the Canadian experts reported seismic activity, bedding soil type and backfill material as the most important factors in the deterioration of water pipelines, while the experts from Qatar chose bedding soil type, seismic activity and disturbance as the most significant. Furthermore, water pressure and O&M practices were determined as the operational parameters that affected the deterioration of water pipelines most in Qatar, while these were determined by the Canadian experts to be water pressure and pH. Computed global weight of importance for each category is multiplied by the local weight of importance of each sub-category to find the total weights of importance for each factor. It can be seen that the criteria of pipe material, pipe installation, pipe age, pipe lining and coating, dissimilar metals and pipe wall thickness are the most important factors in pipeline deterioration, determined by the FAHP method by the Qatari experts. On the other hand, the Canadian experts stated that water pressure, seismic activity, bedding soil type, water pH, disturbance and O&M practices are the most significant parameters in deterioration. As can be seen from Figure 3, the influential parameters in Qatar are completely different from those in Canada. The weights of importance of the physical parameters, as estimated by the Qatari experts, are more than two times those of the Canadian experts. This is reversed for the operational factors, according the expert's opinions.

Table 1. Total weights of importance for all parameters in FAHP

Category	Factors	Canada			Qatar		
		Global weights	Local weights	Weights of importance	Global weights	Local weights	Weights of importance
Physical	Pipe material	0.3589	0.1773	0.0416	0.4207	0.1950	0.1030
	Pipe installation		0.1389	0.0353		0.1622	0.0857
	Pipe age		0.1553	0.0380		0.1457	0.0770
	Pipe lining/coating		0.1379	0.0351		0.1328	0.0702
	Pipe wall thickness		0.1319	0.0341		0.1283	0.0678
	Dissimilar metals		0.1261	0.0331		0.1294	0.0684
	Type of joints		0.1322	0.0342		0.1060	0.0560
Environmental	Bedding soil type	0.3085	0.2344	0.0943	0.3153	0.2257	0.0639
	Backfill material		0.1740	0.0700		0.2108	0.0597
	Soil pH		0.1491	0.0600		0.1631	0.0462
	Seismic activity		0.2405	0.0967		0.2166	0.0613
	Disturbance		0.2015	0.0810		0.1835	0.0519
Operational	Water pressure	0.3325	0.3151	0.1093	0.2636	0.3448	0.0652
	O&M practices		0.2153	0.0747		0.2551	0.0483
	Leakage		0.2065	0.0716		0.1853	0.0351
	Water pH		0.2625	0.0910		0.2143	0.0405

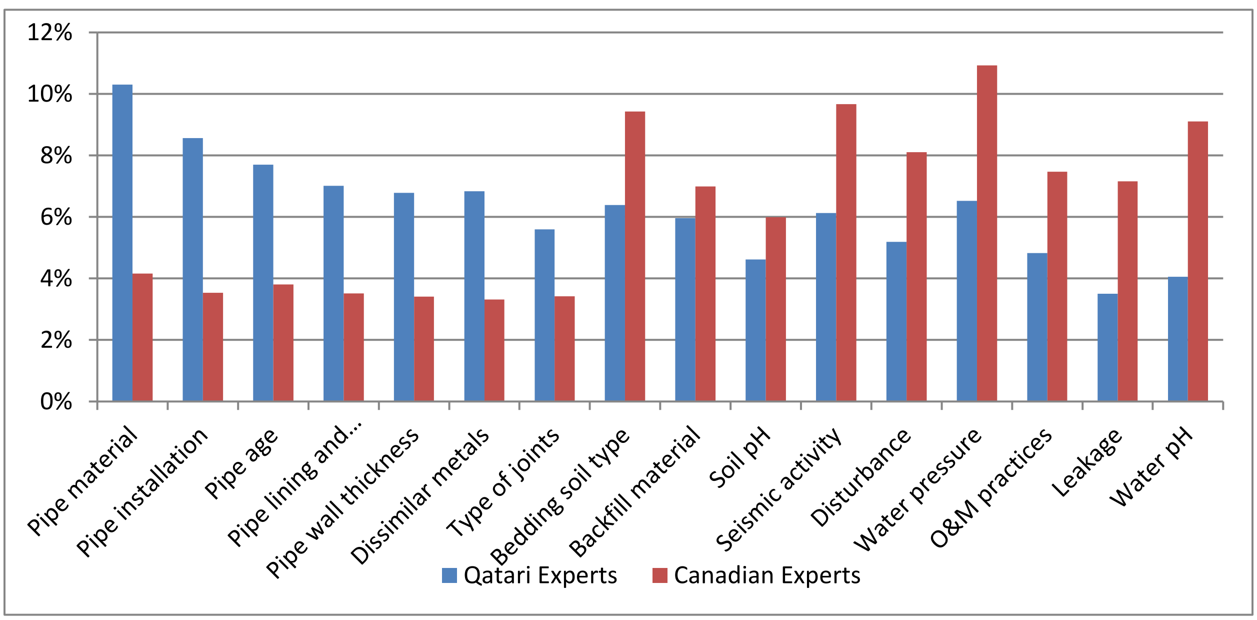

Figure 3. Weights of importance for all parameters through FAHP for both groups of experts

Consistency was checked for the pairwise comparison matrices to verify whether the responses of the experts were consistent, and the results are summarized in Table 2. It can be seen that the consistency ratio for all of the pairwise comparison matrices is less than 10%, which proves that the judgement matrices are reasonably consistent.

Table 2. Consistency in pairwise matrices

	Canada		Qatar	
Pairwise comparison matrix	CI	CR	CI	CR
Global weights	0.0530	0.0914	0.0583	0.1005
Physical factors	0.0425	0.0473	0.0524	0.0418
Environmental factors	0.0531	0.0402	0.0550	0.0416
Operational factors	0.0549	0.0491	0.0647	0.0674

The collected responses were also analysed using the entropy method. The entropy, degree of diversification and weight of importance of the deterioration factors and the comparison of weights are shown in Table 3.

Table 3. Entropy, degree of diversification and weight of importance of the factors

Location	Canada			Qatar		
Criteria/Responses	e_j^*	d_j	w_j	e_j^*	d_j	w_j
Pipe material	0.7447	0.2553	0.0602	0.9579	0.0421	0.0676
Pipe installation	0.7460	0.2540	0.0599	0.9661	0.0339	0.0544
Pipe age	0.7373	0.2627	0.0620	0.9696	0.0304	0.0489
Pipe lining and coating	0.7417	0.2583	0.0610	0.9621	0.0379	0.0608
Pipe wall thickness	0.7384	0.2616	0.0617	0.9638	0.0362	0.0582
Dissimilar metals	0.7362	0.2638	0.0622	0.9757	0.0243	0.0390
Type of joints	0.7410	0.2590	0.0611	0.9457	0.0543	0.0872
Bedding soil type	0.7325	0.2675	0.0631	0.9707	0.0293	0.0470
Backfill material	0.7369	0.2631	0.0621	0.9791	0.0209	0.0335
Soil pH	0.7447	0.2553	0.0602	0.9804	0.0196	0.0315
Seismic activity	0.6979	0.3021	0.0713	0.9154	0.0846	0.1359
Disturbance	0.7389	0.2611	0.0616	0.9524	0.0476	0.0764
Water pressure	0.7352	0.2648	0.0625	0.9615	0.0385	0.0618
O&M practices	0.7383	0.2617	0.0618	0.9598	0.0402	0.0645
Leakage	0.7234	0.2766	0.0653	0.9714	0.0286	0.0459
Water pH	0.7290	0.2710	0.0640	0.9456	0.0544	0.0873

*e_j = entropy
d_j = degree of diversification
w_j = weight of importance

As can be seen from Figure 4 and in the case of determining objective weights, the differences between the estimated weights from both groups of experts vary from 0.5 to 2.5% in the physical factors. Qatari experts believed that the type of joints is the most important physical factor in deterioration, while Canadian experts believed that all of the physical factors have the same importance. This trend was repeated for the Canadian experts in the case of operational factors, while the Qatari experts believed that water pH has the highest effect on deterioration in this category. Both experts believed that seismic activity has the biggest impact in deterioration in the category of environmental factors; however, each group assigned different weights. It can be seen that seismic activity, water pH and type of joints were the most significant factors in the opinion of the Qatari experts, while the Canadian experts believed that seismic activity, leakage and water pH affect the deterioration process the most.

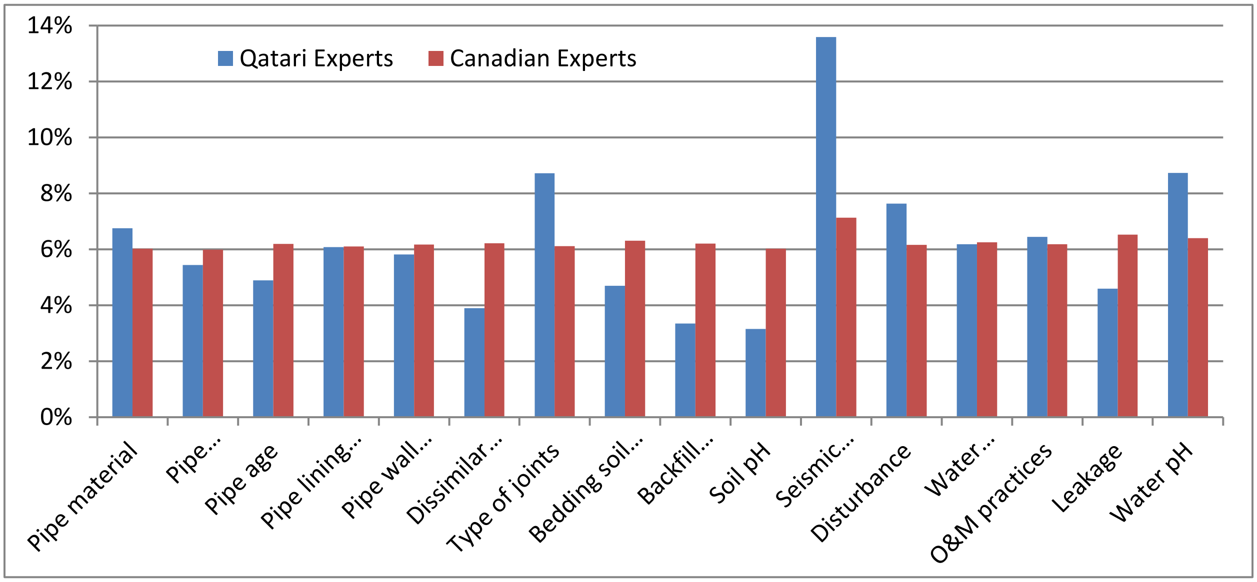

Figure 4. Weights of importance for all parameters through entropy for both experts

The final weight will be the integration of both methods of FAHP and Shannon entropy. Equation 11 is used to find the weights of importance for each parameter. Results are summarized in Table 4 for each factor according to both groups of experts, and the weights of importance from the integration of the two methods are illustrated in Figure 5.

Table 4. Weights of factors from entropy and FAHP

Criterion	Canada	Qatar
Pipe installation	0.0397	0.1120
Pipe age	0.0335	0.0749
Pipe material	0.0374	0.0605
Dissimilar metals	0.0339	0.0686
Pipe lining and coating	0.0334	0.0634
Pipe wall thickness	0.0327	0.0429
Type of joints	0.0331	0.0785
Seismic activity	0.0943	0.0483
Bedding soil type	0.0689	0.0321
Backfill material	0.0573	0.0234
Disturbance	0.1093	0.1339
Soil pH	0.0791	0.0638
Water pH	0.1082	0.0648
O&M practices	0.0731	0.0501
Water pressure	0.0741	0.0259
Leakage	0.0922	0.0569

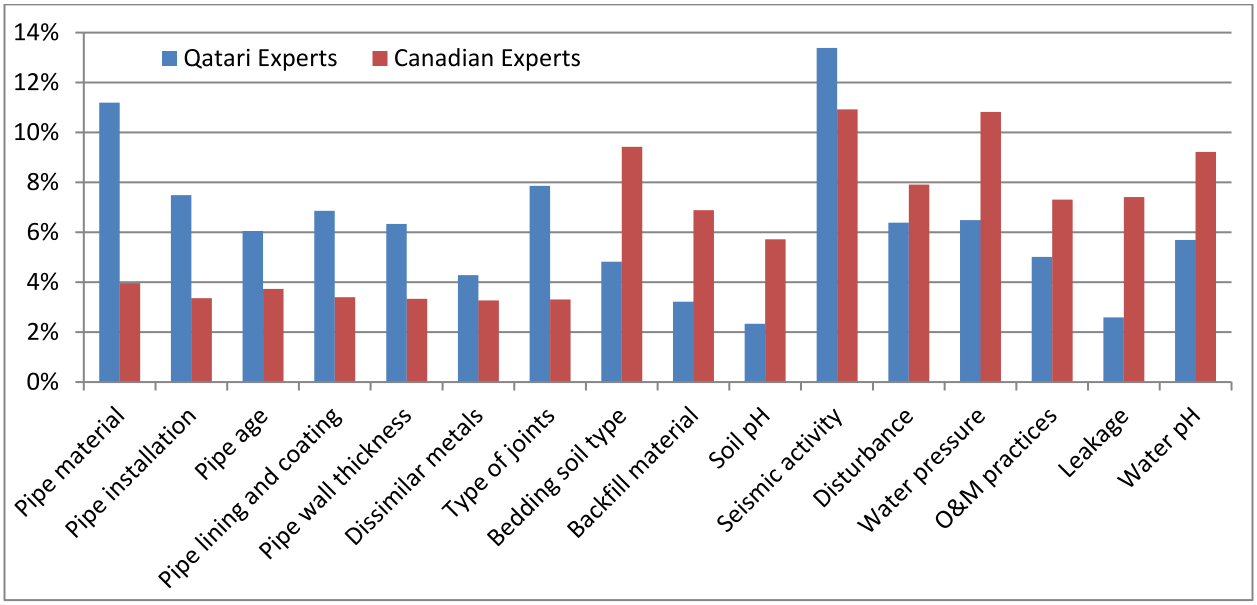

Figure 5. Weights of importance through integration of FAHP and entropy

It can be seen that the prediction of weight of importance for most of the criteria are completely dissimilar, and the differences vary from 1 to 7%. The highest difference is for pipe material for which the Canadian experts predicted the weight of importance as 4%, and the Qatari respondents believed it to be approximately 11%. The lowest difference is for dissimilar metals, for which the Canadian experts estimated the weight of importance as 3%, and the Qatari respondents reported it as 4%. Respondents from Qatar believed that physical factors are more important than operational and environmental parameters, while the Canadian experts allocated more weight to operational and environmental parameters. The Canadian experts believed that seismic activity, bedding soil type, water pressure and pH have the biggest impact on deterioration. On the other hand, the Qatari experts reported that seismic activity, pipe material, type of joints and pipe installation are the most influential parameters in pipeline deterioration. It can be seen that the judgement of experts differed from one location to the other, and the experts considered different weights of importance for each factor.

6 CONCLUSIONS

As pipelines age and subsequently deteriorate, they are increasingly exposed to damage from internal and/or external causes. Recently, the majority of research has focused on the behaviour of WDNs, and several models have been developed to predict the performance of the water infrastructure. Therefore, knowing the impact of physical, environmental and operational factors in the deterioration of water pipeline is essential in order to plan future infrastructure more wisely. This study seeks to determine the effect of location on expert judgement through calculating the weight of importance of the selected factors considering the deterioration process. Two groups of experts were chosen from the two dissimilar locations of Canada and Qatar to determine whether geographical location has an impact on expert judgement. FAHP, Shannon entropy and the integration of the two methods were utilized to determine the weights of importance of each factor. Results show that both groups of experts believe that seismic activity is the most important factor in pipeline deterioration; however, they consider different weights of importance for this factor. The Canadian experts selected operational and environmental factors as the most significant parameters and allocated the highest weight to bedding soil type, water pressure and pH. On the other hand, the Qatari experts chose physical factors as the most important ones, and they reported that pipe specifications, such as material, installation, age, lining and coating and type of joints have the most influence on pipeline deterioration through analysis which should be taken into account while designing durable and reliable pipelines. The outcome of this research also reveals that the experts should be selected specifically from the location where the water networks are placed since the judgement of the experts has been affected by their working experience and current circumstances, such as location and weather. Future works could develop a locality index in order to generalize the expert judgements and opinions from one location to another. The calculated weights of importance from the integration of FAHP and entropy can be used for the future development of models for condition rating and deterioration assessment in Canada and Qatar.

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