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An Integrated Assessment Approach to Prevent Risk of Sewer Exfiltration

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Abstract

Regular inspection, assessment, and rehabilitation are necessary to maintain the performance levels of sewer pipelines. The primary objective of this research is to develop a causality-based model by incorporating twenty-two sewer defects, including erosion voids. The Decision Making Trial Evaluation Laboratory (DEMATEL) was used to study the causality relationship between the defects, based on a designed questionnaire, to conclude the influencing and influenced distress. The results suggested that 59% of the sewer structural and operational defects were influencing ones. Besides, the existing state of the sewer pipelines was evaluated on a scale from 1 (Excellent) to 5 (Critical) by integrating the DEMATEL technique with the Quality Function Deployment (QFD) method. The QFD-DEMATEL model was implemented on a case study to compare the model's classifications of the pipelines' states with the actual ones. Based on the comparison, the average accuracy and true negative rate (TNR) of the classifications were 74% and 79% respectively. Also, the average invalidity percentage (AIP) was 41.32%, causing the validity percentage to exceed 50%. The integrated approach keeps decision-makers informed about their sewer pipelines to prioritize pipelines rehabilitation. Thus, defective sewers are reduced and so are the exfiltration cases.

Keywords: Decision-Making Trial Evaluation Laboratory (DEMATEL), Quality Function Deployment (QFD), sewer pipelines, condition assessment, exfiltration

1. Introduction

Sewer pipelines are indispensable infrastructure components in urban cities (Kaddoura et al., 2017; Duchesne et al., 2013; Vahidi et al., 2016). They transfer sewage from residential, commercial, institutional and industrial resources to wastewater treatment plants (Baah et al., 2015; Selvakumar et al., 2004). However, defects such as cracks, fractures, holes, and breaks will exfiltrate sewage to the surroundings (Ellis et al., 2004; Selvakumar et al., 2004) and hence expose soil, water and the public at large to negative implications (Jaganathan et al. 2010; Costa et al., 2016).

An old study stated that exfiltration in the United States (US) reached up to 30% of the system's flow. However, this number increased to 50% in local areas (US Environmental Protection Agency [EPA], 1989). By that time, the overall sewer network's condition in the US was graded C (American Society of Civil Engineering [ASCE], 1988). With the recent D+ grade of the sewer network in the US (ASCE, 2017), the exfiltration rate is expected to be significant. The Washington Suburban Sanitary Commission estimated 839 sewer overflows annually with 2.5 billion gallons of untreated water flowing into the surrounding environment (District of Columbia Water and Sewer Authority, 2004).

Several studies (Galley et al., 2006; Verlicchi et al., 2012; Meffe and Bustamante, 2014) stated that wastewater that exfiltrates from defective sewer pipelines could result in severe health consequences (e.g. *Salmonella typhi*) due to the contamination of drinking water resources. Sewage contains high levels of suspended solids, pathogenic micro-organism, toxic pollutants, floatables, nutrients, oxygen-demanding organic compounds, oil, grease (US EPA, 2001; Selvakumar et al., 2004), and contaminants of emerging concern (CEC) (Roehrdanz et al., 2017). Moreover, other researchers pointed out that exfiltration causes the water quality standards (WQS) to exceed and/or impact human health through the discharge of pathogens; especially for people residing near lakes or rivers (Selvakumar et al., 2004). Leaky sewers close to surface water could endanger aquatic life forms and their habitats and debilitate the attraction of waterways (Selvakumar et al., 2004). Fish that live in polluted water can carry bacteria "on their scales and in their flesh" and later transfer it to humans, resulting in significant chances of a *Salmonella typhi* infection (Ray, 2002).

Cases of groundwater contamination by sewer related exfiltration have also been reported in several studies. For instance, Bishop et al. (1998) outlined that a total of seventeen sewer-related groundwater contamination incidents in Wales and England led to 3000 reported cases of gastroenteritis infection and 50 cases of typhoid infection between the 1920s and the 1990s. Furthermore, Hunt et al. (2010) studied sewer source contamination of drinking water in several areas in Wisconsin in the US. Based on the 33 sampled wells, 18 tested positive for human enteric viruses. Furthermore, in Rastatt (Germany), the presence of pharmaceuticals and artificial sweeteners were observed, and the mean concentration for 50% of the samples, analyzed over five years, was between 14 ng/l and 702 ng/l (Wolf et al., 2012). The war that began in Yemen in 2015 resulted in the malfunction and collapse of the sewer system, which polluted the drinking water. As a result, 5000 cholera cases were reported daily (Vox, 2017). In fact, more than 360,000 suspected cases of the disease were reported, and 1800 victims had already died.

Given the seriousness of sewage exfiltration from defective sewer pipelines, periodic sewer inspection and rehabilitation is required to maintain satisfactory performance, as pipelines are subject to deterioration. Davies et al. (2001) explained the three stages in which sewer pipelines collapse. According to the authors, the first stage is when cracks are formed due to poor construction practices or overloading disturbance. Due to the presence of groundwater and cracks in the pipeline, infiltration/exfiltration in the system is initiated due to the hydrostatic pressure, which washes out the soil around the pipeline (Jaganathan et al., 2010; Davies et al., 2001). Therefore, the side support is lost, which expedites the deformation of the pipeline, leading to collapse and exfiltration of sewage.

In infrastructure asset management, sewer pipelines are inspected via Closed Circuit Television (CCTV) cameras that are inserted in the system and controlled by an operator. The camera records the inner surface of the pipeline and detects present distress (Feeney et al., 2009). The videos are reviewed by an expert who grades the pipeline according to the detected defects and based on industrial protocols such as the Water Research centre (WRc) and Pipeline Assessment Certification Program (PACP). Nevertheless, the grades supplied by these protocols do not represent the actual state of the pipeline, as they rely on peak and mean scores, which could flatten the observed data (Daher, 2015). Besides, they exclude the assessment of the erosion void defect in sewers, which expedites the propagation of critical sewer structural defects.

Several researchers developed models that assessed the condition of sewers using inspection information and distress observations. For example, Kaddoura et al. (2017) proposed a model that investigated the state of the pipeline by taking the deformation into consideration, along with surface damage, settled deposits, and infiltration defects. The primary technique utilized in their evaluation was the Multi-Attribute Utility Theory (MAUT). Each defect consisted of at least one utility curve that was developed according to protocols and specifications. Although the model provided reliable results, it did not take into consideration many of the sewer defects that could be found in inspection reports. In another work, Daher (2015) adopted the fuzzy expert system, Analytic Network Process (ANP), and Hierarchal Evidential Reasoning (HER), to assess sewer assets including manholes, pipelines, and pipeline joints. Each structural and operational defect was represented by a fuzzy membership function and was then defuzzified into one crisp index representing the condition of the pipeline. Nevertheless, the model lacked the erosion void defect that causes other defects to propagate (Davies et al., 2001). Angkasuwansiri and Sinha (2014) assessed sewer pipelines by suggesting a performance index that took into consideration the structural and operational degradation of the pipeline. Two methods were separately adopted in their assessment: the fuzzy expert system and the weighted average method. Similar to previous research, the authors did not incorporate the erosion void defect and many of the input variables are difficult to obtain (Kaddoura et al., 2017).

Despite the advancements in inspection technologies and condition assessment models, sewer conditions are still degrading in an unanticipated manner. The misinterpretations of the distress observations and the limitations of some current practices hinder rehabilitation plans (Daher, 2015). Therefore, the paramount objective of this research is to develop a causality-based assessment model for sewer pipelines by integrating the Quality Function Deployment (QFD), and the Decision-Making Trial and Evaluation Laboratory (DEMATEL) methods. The objective is accomplished after a) evaluating the structural (including erosion void) and operational sewer defects based on severity measures; b) classifying the influencing and influenced sewer defects, and c) aggregating the influence power weight of each distress in the calculation of the sewer pipelines' grades using a scale that goes from 1 (Excellent) to 5 (Critical). The proposed model will enhance the assessment of sewer pipelines and will keep decision-makers informed about the state of the pipelines to plan preventive maintenance in order to avoid sewage exfiltration (Roehrdanz et al., 2017).

2. Methods

2.1 QFD

The QFD technique is utilized to convert customer needs into technical requirements in each stage of product development (Sullivan, 1986). It is conducted to attain several quality issues' objectives (Chan and Wu, 2002), such as:

1- To improve the quality of the design.
2- To provide planned quality control charts before the initial production run.

The method was initially developed in Japan in 1966 by Yoji Akao but was not formalized in quality control planning until 1972 (Costa et al., 2000). Since then, the QFD approach spread rapidly across Japan and the US (Costa et al., 2000). The QFD is a Total Quality Management (TQM) concept as it requires the inclusion of the customer needs into the project design targets, apart from the essential projects' requirements (Dikmen et al., 2005). It focuses on implementing the voice of the customer after assessing their needs, which are usually determined through interviews, surveys and/or focus groups to ensure their satisfaction (Dikmen et al., 2005).

The formulation of the QFD approach starts with the determination of the product policy and the end-user needs. Therefore, design requirements are established to form the "WHAT's," which in turn establishes the component characteristics "HOW's" of the product design. A matrix is then constructed to study the relationship between the HOW's and the WHAT's (Costa et al., 2000). After that, the absolute weights are determined by aggregating the HOW's and WHAT's through the use of the factors in the matrix established earlier. Consequently, the House of Quality (HOQ) is then finalized; a general representation is shown in Fig. 1.

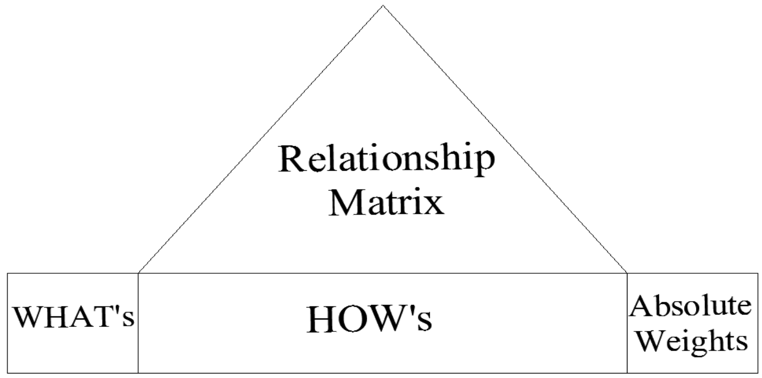


Fig. 1. HOQ General Representation

The QFD utilization was restructured to suit its application in the infrastructure condition assessment. Thus, in the context of this research, each component was considered as follows (Alsharqawi et al., 2016):

- WHAT's was the condition severity. In this research, five different severities were considered: Excellent, Good, Fair, Poor, and Critical. These severities reflected the asset's condition.
- HOW's represented the defects considered in each asset under assessment in a percentage form, as shown in Table 1. The table describes each defect and grade and their definitions. The grades range between 1 to 5, where 1 expresses a noncritical defect and 5 describes a critical defect. The observed defects in the inspected pipelines are recorded and graded according to their severity. Soil loss (erosion void) was added to the model due to the critical role it plays in causing other defects (Davies et al., 2001). Its assessment was accomplished according to the methodology presented by Kaddoura and Zayed (2017), which is discussed in section 2.3. The relationship matrix was the roof component of the QFD approach. It established the relationship between the defects in concern.

- Absolute Weights were the weights of the WHAT's, which were concluded after aggregating the HOW's with each WHAT.
- The HOQ represented the complete application of the QFD in a diagram as in Fig. 1.

Table 1. Sewer Pipeline Defects, Grades, and Description

Number	Pipeline Defects	Description	Grade	Grade Description	
1	Longitudinal Crack	A Line is apparent but not open that is running along the pipeline axis	1	Length <75 mm	
			2	75-150 mm	
			3	>150-225	
			4	>225 - 300 mm	
			5	>300 m	
2	Circumferential Crack	A Line is apparent but not open that is running at right angles to the axis of the pipeline	1	1 clock positions	
			2	2 clock positions	
			3	3-4 clock positions	
			4	5-6 clock positions	
			5	>6 clock positions	
3	Multiple Crack	Combination of longitudinal and circumferential cracks	1	Length <75 mm	
			2	75-150 mm	
			3	>150-225	
			4	>225 - 300 mm	
			5	>300 m	
4	Longitudinal Fracture*	An open crack that is running along the pipeline axis	1	Length <75 mm	Width <1.5 mm
			2	75-150 mm	1.5 mm to 5
			3	>150-225	5 to 8 mm
			4	>225 - 300 mm	8 to 16 mm
			5	>300 m	> 16 mm
5	Circumferential Fracture*	An open crack that is running at right angles to the axis of the pipeline	1	1 clock positions	Width <1.5 mm
			2	2 clock positions	1.5 mm to 5
			3	3-4 clock positions	5 to 8 mm
			4	5-6 clock positions	8 to 16 mm
			5	>6 clock positions	> 16 mm

Number	Pipeline Defects	Description	Grade	Grade Description	
6	Multiple Fracture*	Combination of longitudinal and circumferential fractures	1	Length <75 mm	Width <1.5 mm
			2	75-150 mm	1.5 mm to 5
			3	>150-225	5 to 8 mm
			4	>225 - 300 mm	8 to 16 mm
			5	>300 m	> 16 mm
7	Deformation	When the cross-section of the pipeline is altered horizontally or vertically	1	Deformation < 2.5%	
			2	2.5% and < 5%	
			3	5 and <7.5%	
			4	7.5 and <15%	
			5	>= 15%	
8	Hole	A visible hole in the pipeline	3	1 clock position	
			4	2 clock positions	
			5	>=3 clock positions	
9	Break	Pieces are noticeably displaced in the pipeline wall	3	1 clock position	
			4	2 clock positions	
			5	>=3 clock positions	
10	Sag	When pipeline slope changes; it can be detected through ponds	1	<5%	
			2	5 and <10%	
			3	10 and <25	
			4	25 and <50	
			5	>=50	
11	Collapse	Loss of structural integrity of the pipeline	5	Pipeline Collapsed	
12	Surface Damage	Pipeline surface is changed from its original condition (loss of wall thickness)	1	0-10% thickness loss or increased roughness	
			2	<10%-20% or spalling	
			3	<20%-30% or aggregate visible or projecting, missing mortar	
			4	30%-<50% or aggregate missing, displaced brick	
			5	>=50% or reinforcement visible or corroded, missing brick	
13	Settled Deposits	Materials in a sewer pipeline which could cause flow turbulence	1	0-5%	
			2	<5-10%	
			3	<10-20%	

Number	Pipeline Defects	Description	Grade	Grade Description
		and reduction of cross-section (i.e., debris)	4	<20-30%
			5	>30%
14	Soil Deposits	Presence of soil from pipeline inlets or surrounding ground; causing turbulence in the flow	1	0-5%
			2	<5-10%
			3	<10-20%
			4	<20-30%
			5	>30%
15	Roots	Ingress of roots through defects	1	0-5%
			2	<5-10%
			3	<10-20%
			4	<20-30%
			5	>30%
16	Infiltration	Ingress of groundwater through defects	1	<6 ml/min
			2	6-500 ml/min
			3	>500 ml/l-5 l/min,
			4	>5 l/min 10 l/min
			5	>10 l/min
17	Obstruction	An obstacle in the drain	1	0-5%
			2	<5-10%
			3	<10-20%
			4	<20-30%
			5	>30%
18	Offset Joint	A pipe is not concentric with the socket of the adjacent pipe	1	0 to 6% of pipe diameter
			2	>6 -12 of pipeline diameter
			3	>12 to 18% of pipeline diameter
			4	>18% to 25% of pipeline diameter
			5	>25% of pipeline diameter
19	Open Joint	Adjacent pipelines which are longitudinally displaced at the joint	1	> 0 to 12 mm
			2	>= 12 mm and < = 25 mm
			3	>25mm and <= 50mm
			4	>50mm and <=100mm
			5	>100 mm
20	Soil Loss (Erosion Void)	Loss of soil support around the pipeline	1	Excellent
			2	Good
			3	Fair
			4	Poor
			5	Critical

Number	Pipeline Defects	Description	Grade	Grade Description
21	Attached Deposits	Foreign materials that are attached to the sewer pipeline and continue to accumulate	1	0-5%
			2	<5-10%
			3	<10-20%
			4	<20-30%
			5	>30%
22	Protruding Service	Objects that have been inserted after construction	1	0-5%
			2	<5-10%
			3	<10-20%
			4	<20-30%
			5	>30%

** Consider the maximum grade between length and width. For example, if the grade of a crack length is 4 and the grade of a crack width is 3, select 4.*

2.2 DEMATEL

The DEMATEL approach was developed by the Science and Human Affairs Program of the Battelle Memorial Institute of Geneva between 1972 made 1976, to solve complicated problems (Tzeng et al., 2007). It is used to understand a specific *problematique* for a cluster of intertwined problems and contribute to the identification of workable solutions by following a hierarchical structure (Tzeng et al., 2007). This method is capable of establishing a relationship of interdependency between the participating variables in a cause and effect concept to conclude the causing and effecting variables (Tzeng et al., 2007). Therefore, the result of the method will find the central components of the problem. This technique is based on a questionnaire that needs to be answered by an expert. The more responses are collected, the more accurate the results are, as they compile the opinions of several professionals in the domain. DEMATEL was utilized according to the following steps:

1- After receiving the responses, the average influence matrix was constructed, which showed the influence of one element in the system to the other. The influence was represented by 0, 1, 2, 3, and 4, which indicated “no influence,” “low influence,” “medium influence,” "high influence," and "extreme influence," respectively. The degree to which the respondents believed that factor *i* was affected by factor *j* was given by the notation x_{ij}. For each respondent, $n \times n$ non-negative matrix could be established as $X^k = [x^k_{ij}]$, where *k* was the number of the participating respondents with $1 \leq k \leq H$, and *n* was the number of the factors. As a result, $X^1, X^2, \ldots, X^H$ were the number of matrices found from each respondent. Therefore, the values of each x_{ij} in each matrix were computed through the average as per equation 1.

$$a_{ij} = \frac{1}{H}\sum_{k=1}^{H} x_{ij}^{k} \tag{1}$$

The average matrix was then displayed in the HOQ as the top roof triangle, which was initially the correlation matrix. Fig. 2 shows a general average influence matrix of a system comprised of four elements. Taking element 2 and 3 as an illustration, a_{23} is the influence of element 2 on factor 3. However, a_{32} is the influence of element 3 on factor 2. In fact, the zeros in the triangle are the diagonal values of the matrix, which are always zero.

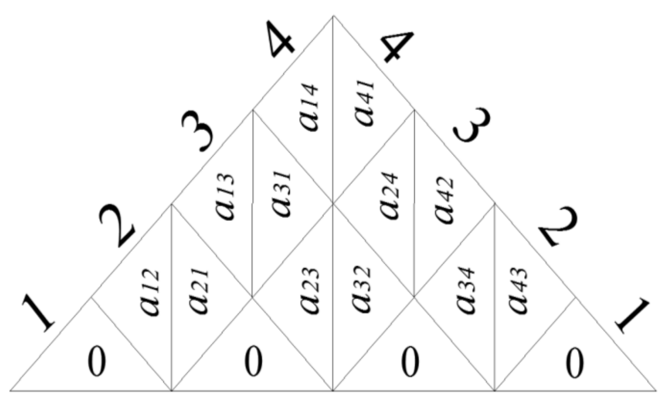


Fig. 2. Relationship Matrix in HOQ

2- Calculate the normalized direct influence relation matrix *D* from the average matrix found in step 1 and according to equation 2. To do so, identify the maximum value, by summing the a_{ij} values in the rows and the columns. This maximum amount was used to compute matrix *D*.

$$S = \frac{1}{\underset{1 \le i \le n}{Max} \sum_{j=1}^{n} a_{ij}} \quad (2)$$

3- Calculate the total relation influence matrix *T* using equation 3.

$$T = D\,(I - D)^{-1} \quad (3)$$

where *I* is the identity matrix. Define *r* and *c* to represent the sum of rows and columns of the total relation matrix *T*, respectively. Consider r_i to be the sum of the *i*th row in matrix *T*, then r_i concluded both the direct and indirect effects given by factor *i* to the other elements. If c_j denoted the sum of the *j*th column in matrix *T*, then c_j showed both direct and indirect effects by factor *j* from the other factors. When $j = i$, the sum $(r_i + c_j)$ showed the total effects given and received by element *i*. In other words, it represented the total cause and effect relationship in the whole system. However, the difference $(r_i - c_j)$ translated the net effect that factor *i* contributed to the system. If the value computed was positive, the factor was a cause. On the other hand, if the calculated value was negative, the element was an effect.

4- Consider setting up a threshold to filter out negligible effects. In this research, setting up a threshold was not considered as all participating elements were significant in assessing the condition of the sewer assets.

5- Next, the normalized influence matrix was assembled, which derived the total influence matrix. As a result, the cause and effect contribution of each element in the system was consummated. Subsequently, influencing and influenced elements were categorized accordingly.

2.3 Erosion Void Assessment

The CCTV inspection technique fails to provide information about the state of the soil surrounding sewer pipelines; as a result, current practices neglect it during assessment. Due to this limitation, this study used the model suggested by Kaddoura and Zayed (2017) that assessed the erosion void defect. The model relied on some characteristics of the pipelines to check the adequacy of the surrounding soil. This information is always available in any inspected pipeline's report.

The authors identified five different factors that influence the development of the erosion void distress, such as the groundwater presence, bedding type, soil type, pipeline depth, and age. A triangular fuzzy membership function represented each factor except for the discrete attribute values. The grade, which ranges between 1 (excellent soil support) and 5 (critical soil support), was calculated based on the weighted average defuzzification method. In this study, the characteristics of the pipelines were extracted from the CCTV reports and the erosion void grade was computed after using the fuzzy membership function of each factor. To consider the erosion void defect in the developed assessment model, the crisp value (grade) computed from the assessment model of Kaddoura and Zayed (2017), was fuzzified according to Fig. 3. The figure shows a triangular fuzzy membership function for the similar severity grades considered in this study (Excellent, Good, Fair, Poor, and Critical). These states were used to fuzzify the grade into a percentage form to incorporate it in the HOQ. For example, the erosion void grade of an eighty years old pipeline, surrounded by coarse aggregate sand, located below the water table, and laid above class B bedding at a depth of 6 m is 2.99. Subsequently, the computed erosion void grade is fuzzified, using Fig. 3, to 49% (Poor) and 51% (Fair). These two percentages are considered as an evaluation scheme of the erosion void defect in the HOQ table.

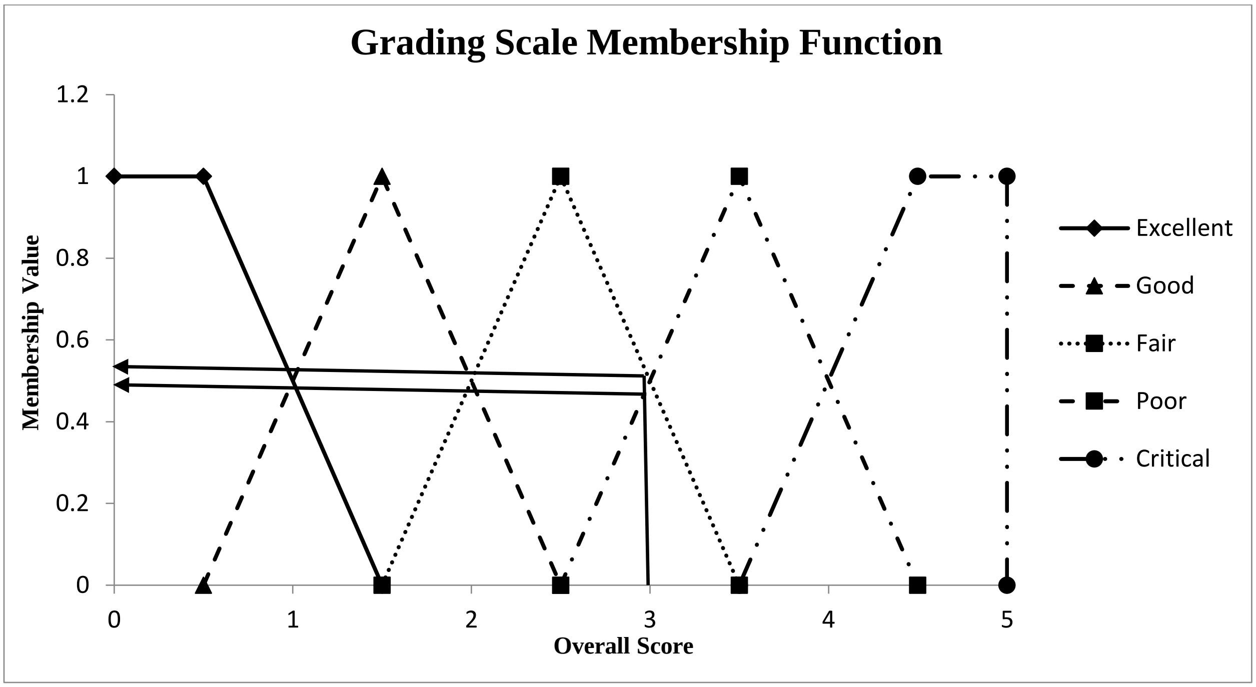


Fig. 3. Erosion Void Grade Fuzzy Membership Function

2.4 Overall Pipeline Grade Calculation

The application of the QFD-DEMATEL method supplied five different percentage severities, where the relative weights were then found to calculate the overall grade of the asset. The overall grade of the pipeline was computed by aggregating the grades' percentages with the value of the grade condition as per equation 4.

$$\text{Overall Pipeline Grade} = \sum_{1}^{5} RW_i * i \quad (4)$$

where *RW* is the relative weight of each grade found, and *i* is the weight of each condition severity. For example, Excellent is 1; Good is 2; Fair is 3; Poor is 4, and Critical is 5. The grade description is interpreted in Table 2. For example, if the calculated grade of a pipeline was 1.74, that pipeline would be classified as Good. Based on the description, the pipeline had minor defects with small to medium severities.

Table 2. Proposed Pipeline Overall Grades, Conditions and Descriptions

Overall Grade	Condition	Description
1.00 to <1.50	Excellent	No defects with strong soil support
1.50 to < 2.00	Good	Minor defects are observed with small to medium severities; soil support erosion started with minimal severity
2.00 to < 3.00	Fair	Moderate defects with medium severity; soil erosion is in progress
3.00 to <4.00	Poor	Major defects with medium to high severity; void erosion is severe
4.00 to 5.00	Critical	Severe defects are observed. Pipeline collapses or collapse is imminent. Pipeline has lost a majority of its surrounding soil

2.5 Statistical Analysis

Table 2 was used to classify the pipelines according to the five condition groups; the calculated grades and the actual grades were classified into Excellent, Good, Fair, Poor, and Critical. The accuracy metric was used to test the accuracy of the model in classifying the pipelines' conditions when compared to the actual groupings. Besides, the true positive rate (TPR) and true negative rate (TNR) were utilized to check the capability of the model in distinguishing between positive and negative classifications. After comparing the predicted classifications with the actual ones, a confusion table, for each condition, was prepared to extract the inputs of equations 5, 6, and 7

(Peleato et al., 2017). The three indicators were calculated after finding the true positive (TP), true negative (TN), false positive (FP), and false negative (FN) of each condition from its corresponding confusion table. TP represented the number of correctly classified conditions when compared with the actual ones (estimated: Excellent; actual: Excellent). In the confusion table of the Excellent condition, the TN showed the correct rejection of the classification when compared to the actual data (estimated: Good, Fair, Poor, and Critical; actual: Good, Fair, Poor, and Critical). However, FP described the incorrect classification of the model (estimated: Excellent; actual: Good, Fair, Poor, and Critical). FN explained the number of conditions that the model failed to classify although they were observed (estimated: Good, Fair, Poor, and Critical; actual: Excellent). Higher values of TPR describes a more reliable model in positively classifying the conditions and vice versa. Also, higher values of TNR mean that the model can negatively classify the conditions. Similarly, higher values of accuracy denote a more accurate model.

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN} \quad (5)$$

$$TPR = \frac{TP}{TP + FN} \quad (6)$$

$$\text{TNR} = \frac{TN}{FP + TN} \quad (7)$$

The condition assessment model was also validated with the actual grades that were obtained from the city of Edmonton. Equation 8 shows the average invalidity percentage (AIP) to deduce the validity of the model. The lower the value of AIP, the higher the validity of the model (Al-Barqawi and Zayed, 2006). Also, the root mean square error (RMSE) and the mean absolute error (MAE) are estimated according to equations 9 and 10, respectively (Al-Barqawi and Zayed, 2006). These two parameters express the average model prediction error in the units of the variable; therefore, lower values correspond to a better model. The input parameters for the equations were the estimated grades (E), the actual grades (C), and the number of pipeline samples (n).

$$AIP = \frac{\sum_{i=1}^{n} \left|1-\left(\frac{E_i}{C_i}\right)\right|}{n} * 100 \quad (8)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(C_i - E_i)^2}{n}} \quad (9)$$

$$MAE = \frac{\sum_{i=1}^{n}|C_i - E_i|}{n} \quad (10)$$

3. Data Collection

3.1 Questionnaire

A questionnaire was prepared and distributed to professionals in the field of sewer asset management, similar to Fig. 4. The practitioners were sought from different municipalities, consulting companies, and research institutions through their professional and academic profiles found online. This questionnaire was pertinent to the deployment of the DEMATEL method in finding the influence power between the elements in the system. As a result, the experts could decide the bidirectional influence power between any two defects. For instance, if a participant believes fractures have higher influence power on infiltration, the participant will choose 4 in the X to the Y direction.

X	No Influence	Low Influence	Medium Influence	Extreme Influence	High Influence	Y
Fracture	0	1	2	3	4	Infiltration
	→	→	→	→	→	
	←	←	←	←	←	
	4	3	2	1	0	
X	High Influence	Extreme Influence	Medium Influence	Low Influence	No Influence	Y

X	No Influence	Low Influence	Medium Influence	Extreme Influence	High Influence	Y
Roots	0	1	2	3	4	Infiltration
	→	→	→	→	→	
	←	←	←	←	←	
	4	3	2	1	0	
X	High Influence	Extreme Influence	Medium Influence	Low Influence	No Influence	Y

Fig. 4. A Sample of a Questionnaire between Three Defects

About 90% of the 115 questionnaires were sent to professionals and responses received via e-mail, and the remaining were distributed physically as a hard-copy. Fortunately, 28% of the distributed questionnaires were received; specifically, thirty-two experts participated from four different regions: North America (Canada and US), Middle East, Europe and China. The respondents' years of experience varied as displayed in Fig. 5. As shown in the figure, the highest number of responses was from the participants with experience between 9 and 15 years. However, the lowest number of the responses was from the participants with experience between 3 and 6 years. Besides, the participants from North America responded the most when compared to the other areas; while the Middle East region's respondents were the lowest participants as shown in Fig. 6. This was expected, since the practices of sewer condition assessment and trenchless technology are not as popular in the Middle East when compared to the other regions. The responses were then analyzed to compute the average influence matrix. It was prepared by finding the mean of each influence between any two defects. For example, if participant *a* and *b* gave an influencing power of 3 and 2, respectively, between defect X and Y, the average influence would be 2.5.

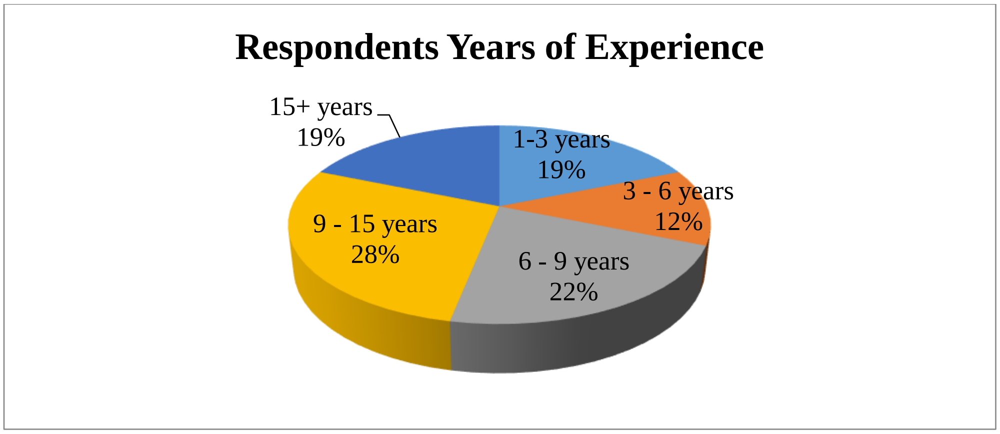


Fig. 5. Respondents Years of Experience

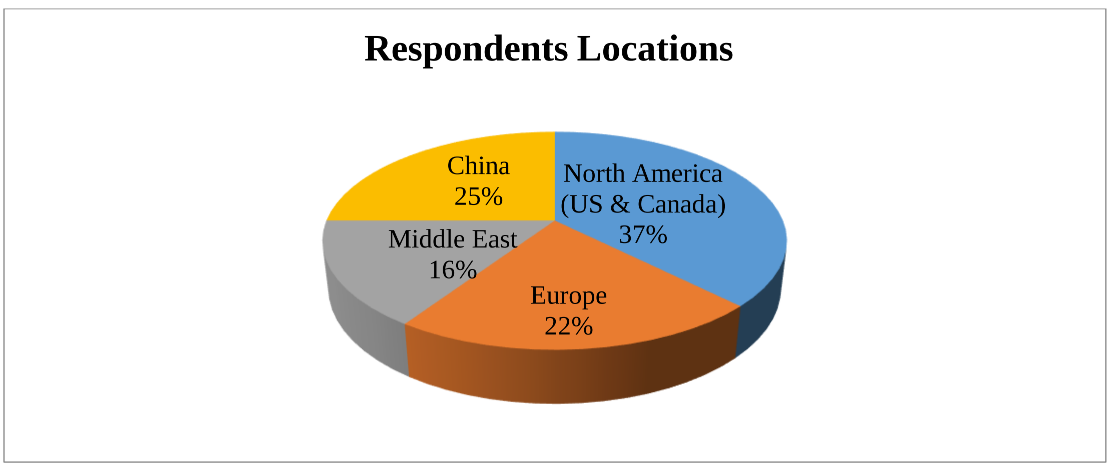


Fig. 6. Respondents Locations

3.2 Study Area

The developed models were implemented and tested on the Royal Gardens' sewer network, located in the city of Edmonton, Canada. The information received consisted of 481 sewer pipelines as displayed in Fig. 7. The database included general information about the pipelines, such as the year of construction, depth, material type used, etc. Besides, 4067 defects/observations were reported in the database according to PACP coding system. The distress observations were used in the integrated QFD-DEMATEL approach to calculate the grades. The erosion void conditions were also calculated according to the methodology of Kaddoura and Zayed (2017), by taking into consideration the pipelines' information. Subsequently, the reported grades of the pipelines from the city were used as a baseline to validate the model.

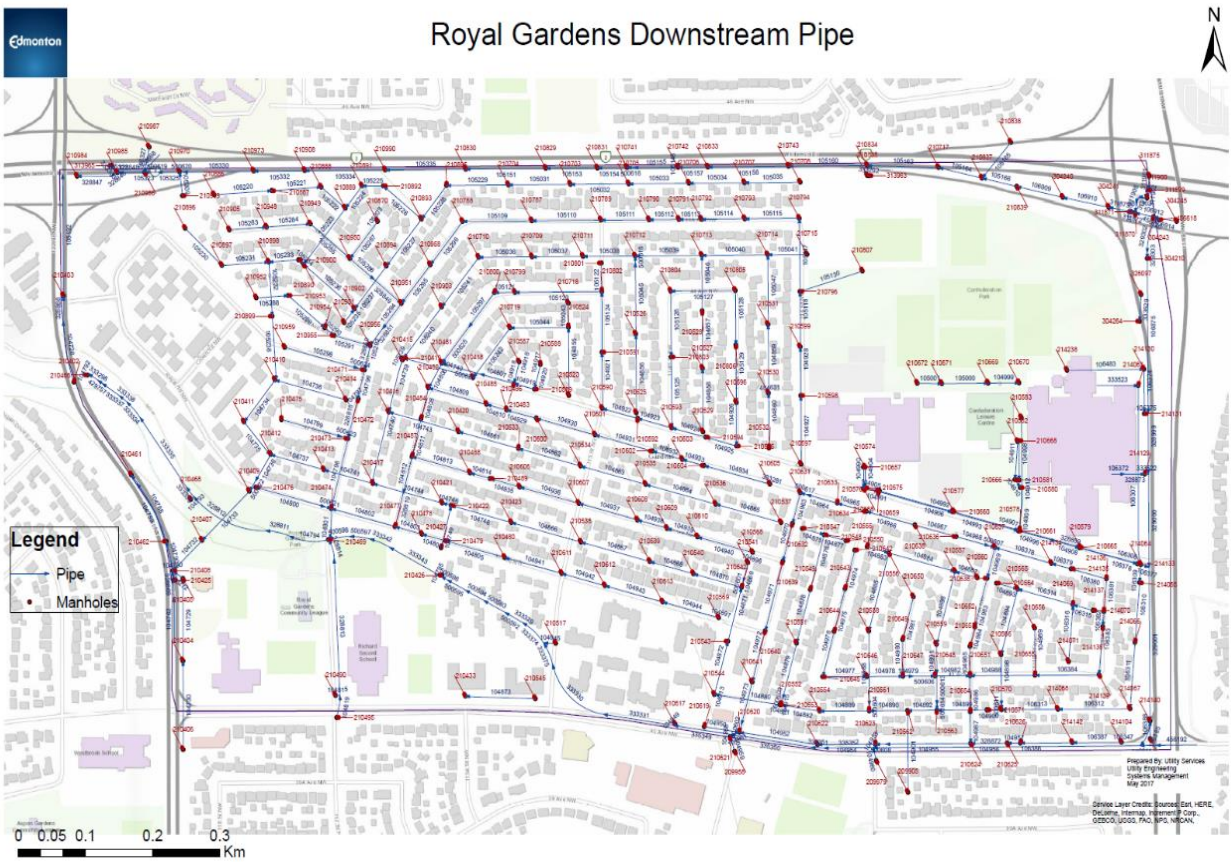
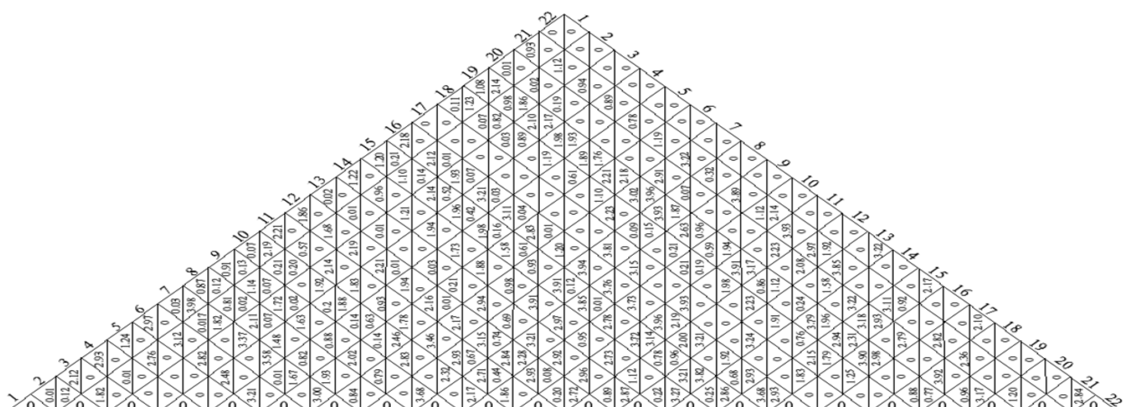


Fig. 7. Royal Gardens Sewer Network Layout

4 Results and Discussions

4.1 DEMATEL-QFD Model

Based on the response to the questionnaire received from the experts, the influence matrix in the HOQ of the pipeline was developed and is shown in Fig. 8. For example, defect number 1, longitudinal crack, had an influence of 0.03 on defect number 7 (deformation); however, deformation defect had an influence of 3.98 on longitudinal cracks. Based on the results, the deformation defect was significantly influencing the propagation of the longitudinal crack as reported by Davies et al. (2001). However, the longitudinal crack had minimal to no influence on causing the deformation distress, according to the average influence matrix. On the other hand, when comparing the defect number 2 (circumferential crack) with the defect number 7, the deformation defect had an influence rating of 1.82 on the propagation of the circumferential crack, which was apparently lower than the influence of deformation on the longitudinal crack. It was true, since longitudinal cracks initiate due to structural deficiencies; however, circumferential cracks propagate due to construction faults and are not as critical as the longitudinal ones.



		Long. Crack	Circ. Crack	Multiple Crack	Long. Fracture	Circ. Fracture	Multiple Fracture	Deformation	Hole	Break	Sag	Collapse	Surface Damage	Settled Deposits	Ingress of Soil	Roots	In/exfiltration	Obstruction	Offset Joint	Soil Support Loss	Open Joint	Attached Deposits	Prot. Service
		1.23	0.93	1.26	1.22	1.01	1.52	2.02	1.72	1.79	1.55	2.41	2.02	1.69	1.74	2.78	2.48	0.76	1.14	3.13	1.20	1.68	0.33
	#	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Severity	Relative Influence Weight	0.035	0.026	0.035	0.034	0.028	0.043	0.057	0.048	0.050	0.044	0.068	0.057	0.047	0.049	0.078	0.070	0.021	0.032	0.088	0.034	0.047	0.009
Excellent	1	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Good	2	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	85.00%	0.00%	0.00%	0.00%
Fair	3	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	15.00%	0.00%	0.00%	0.00%
Poor	4	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Critical	5	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Excellent	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Good	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	85	0	0	0
Fair	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15	0	0	0
Poor	4	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Critical	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Fig. 8. QFD-DEMATEL Model

After finding the average influence matrix, the normalized influence matrix was computed by comparing the maximum summation of each column and row. The highest number was taken and divided by the values in the average influence matrix. Table 3 summarizes the computations of the DEMATEL approach. Based on the table, the value of C+R of each defect represented the impact of an element, considering its cause and effect power, in the system. Consequently, the "Weight" column was the relative total influence of the defect in the system and was computed from the C+R column. According to the same table, the voids present outside the pipeline had the highest weight due to their significant influence (Davies et al. 2001). The cumulative influence of the defects influenced by the erosion void was amalgamated in the high relative influence weight. However, the least relative weight was for the protruding service, as it exists in the system due to design and construction faults.

The R-C column, as seen in Table 3, distinguishes the influencing and influenced defects. Any value that was less than zero was considered as an influenced defect; while any value that was greater than zero was deduced to represent an influencing defect. Based on the results, the percentage of influencing defects in the system was 59% and included cracks, longitudinal and circumferential fractures, deformation, holes, breakage, sag, offset joint, open joint, erosion voids, and protruding services. However, the remaining 45% were influenced ones. Most of the identified influencing defects supported the conceptual representation of the sewer pipeline collapse process presented by Davies et al. (2001).

On the other hand, the developed model by Daher (2015) was mostly influenced by the evaluations of the current practices disregarding the impact of the causality relationship between the defects. According to the author, the multiple fractures were relatively more important than a broken pipeline. Besides, the same study reported almost similar relative importance weights between multiple fractures and deformation defects. Based on these results, pipeline X with multiple fractures of grade 5 and pipeline Y with a deformation of a similar grade will be rated as Critical. Yet, the consequences of deformed pipelines compared to multiple fractures defects are far more severe, since deformation could lead to collapse and sewage exfiltration (Motahari and Abolmaali, 2009). Although Kaddoura et al. (2017) explained the importance of deformation, settled deposits, infiltration, and surface damage defects, the developed assessment was not applicable to pipelines having defects other than the considered ones.

Table 3. Influence Power and Weights of the Sewer Defects

Number	Sum of Columns	Sum of Rows	C+R	R-C	Weight
1	0.87	0.36	1.23	0.51	0.035
2	0.73	0.20	0.93	0.53	0.026
3	0.81	0.45	1.26	0.36	0.035
4	0.80	0.41	1.22	0.39	0.034
5	0.70	0.31	1.01	0.39	0.028
6	0.74	0.78	1.52	-0.05	0.043
7	1.79	0.23	2.02	1.55	0.057
8	1.04	0.68	1.72	0.36	0.048
9	1.22	0.56	1.79	0.66	0.050
10	1.21	0.34	1.55	0.87	0.044
11	0.97	1.44	2.41	-0.47	0.068
12	0.56	1.45	2.02	-0.89	0.057
13	0.35	1.34	1.69	-0.98	0.047
14	0.34	1.40	1.74	-1.06	0.049
15	1.05	1.74	2.78	-0.69	0.078
16	0.70	1.78	2.48	-1.08	0.070
17	0.25	0.51	0.76	-0.25	0.021
18	0.89	0.25	1.14	0.64	0.032
19	1.66	1.47	3.13	0.19	0.088
20	0.75	0.45	1.20	0.31	0.034
21	0.21	1.47	1.68	-1.26	0.047
22	0.33	0.00	0.33	0.33	0.009

4.2 Study Area Implementation

Each pipeline had a unique QFD-DEMATEL model, as shown in Fig. 8. The inputs of the model were the defects counts for each pipeline, which were inserted in the second table of the same figure. The percentage of each severity was calculated based on the aggregation of the same severity by the relative influence weight of each defect. As a result, the resulting five different severities of the pipeline were calculated. For a randomly selected pipeline, the report indicated two defects with a PACP grade of 2.50. The first distress was settled deposits; while the second one was a circumferential fracture. Based on the information provided in the report, each defect's severity was compared with the defect information in Table 1. Since the reports did not evaluate the erosion void defect, its severity was computed as illustrated earlier.

The relative influence weights were used to aggregate each severity separately. The pipeline had five severity grades with different percentages as shown in Table 4. Since the Good condition for the erosion void defect was 85%, and considering the high relative influence weight for this defect, the aggregated grade percentage for Good was the highest among the other severities. The relative weights of the condition grades percentages were then used to calculate the overall grade for the pipeline on a scale of 1 to 5 as follows:

Overall Grade = 1*0.1728 + 2* 0.4567 + 3*0.0806 + 4*0.2900 + 5*0.00 = 2.49

Table 4. Sample Pipeline Condition Grades and Overall Grade

Grade	Condition Grade %	Condition Grade Relative Weight %	Overall Grade
Excellent	2.83%	17.28%	2.49
Good	7.48%	45.67%	
Fair	1.32%	8.06%	
Poor	4.75%	29.00%	

Critical	0.00%	0.00%

The conditions of the remaining pipelines were calculated by following the aforementioned methodology. Therefore, 85 HOQs were designed, and the overall grades were calculated. The pipelines were categorized according to their calculated grades, as shown in Fig. 9. The figure suggests that the majority of the calculated overall grades (62%) were Fair, as the grades ranged between 2 and 3. However, 30% of the calculated overall grades were Poor, and 7% of them were Good. Nevertheless, 1% of the estimated overall grades were Excellent. Based on the results, none of the pipelines were in critical condition. The results indicated that many pipelines require maintenance as influencing defects were observed, especially for pipelines in Fair and Poor conditions. These preventive interventions will help prolong the service-life of the pipelines and avoid sudden collapses.

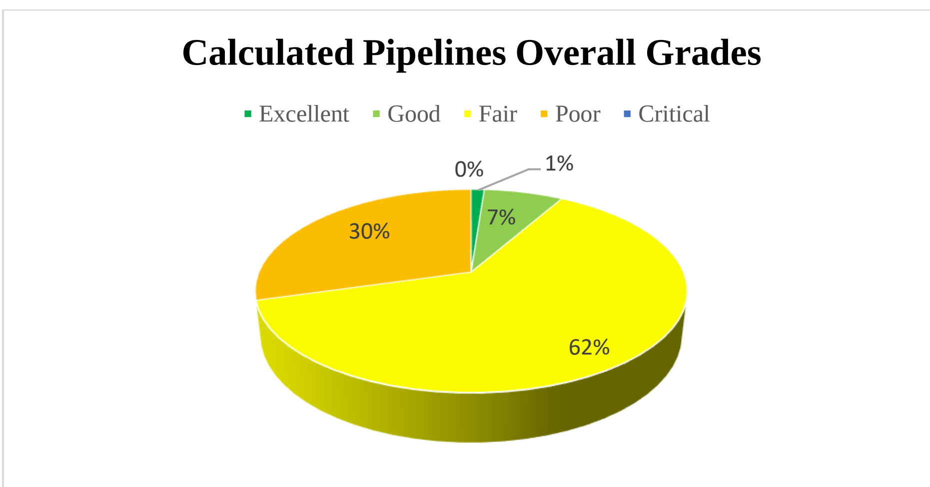


Fig. 9. Royal Gardens Overall Pipelines Conditions

4.3 Statistical Analysis

A detailed comparison between the estimated and actual grades was also established to facilitate extracting the confusion table for each condition. The estimated grades and their corresponding classifications in Table 5 were concluded following the information in Table 2. For instance, the QFD-DEMATEL model classified sixteen pipelines in Fair condition, while the reports claimed that the same pipelines were in Poor conditions.

Table 5. Comparison between Actual and Estimated Conditions

Condition		Actual				
		Excellent	**Good**	**Fair**	**Poor**	**Critical**
Estimated	**Excellent**	0	1	0	0	0
	Good	1	1	3	0	1
	Fair	10	5	22	16	0
	Poor	1	1	15	6	2
	Critical	0	0	0	0	0

Based on Table 5, the confusion matrix for each condition was prepared and used to find the accuracy, TPR, and TNR indicators. As an example, in the confusion matrix values for the Fair category, the TP was twenty-two, FN was eighteen, FP was thirty-one, and TN was fourteen. Accordingly, the three indicators were calculated to test the applicability of the model. The results of the metrics are summarized in Table 6. The average accuracy and TNR percentages were 74% and 79%, respectively. In contrast, the average TPR percentage was 19%. The accuracy and TNR percentages were higher than TPR percentages, as the model was able to correctly classify the TNs, which represented the majority of the population. Although TPR percentages were low, the model could classify several pipelines correctly. The results showed that the current model was conservative since the grades considered both the conventional and the erosion void defects in the assessment. Specifically, the actual data suggested ten pipelines were in an Excellent condition, whereas the estimated conditions were Fair. In other cases, the actual data classified three critical pipelines that were misclassified by the QFD-DEMATEL model. For these particular pipelines, the inspection reports were re-visited and indicated that protruding services defects were present. Based on the model, this defect had the smallest contribution of the pipeline condition.

Table 6. TPR and Accuracy Percentages

Condition	TPR	Accuracy	TNR
Excellent	0%	85%	99%
Good	13%	86%	94%
Fair	55%	42%	31%
Poor	27%	59%	70%
Critical	0%	96%	100%

The condition assessment model was also validated with the actual values obtained from reports by the city of Edmonton. Considering equations 8, 9, and 10, the AIP was 41.32%; the RMSE was 0.89 and the MAE was 0.73. The results suggested that there were deviations from the actual values. It was expected as the model proposed a new methodology in assessing the pipeline condition considering relative influence weights. Besides, the model took into account an essential defect, erosion void, which was not considered under many of the existing protocols.

5 Conclusions

Designing a comprehensive sewer assessment model is an important step for effective asset rehabilitation plans. These actions will certainly reduce collapses and sewage exfiltration. The developed QFD-DEMATEL model investigated multiple structural and operational defects observed in sewer pipelines. The causality-based method classified the identified defects into influencing and influenced defects. Based on the study, 59% of the defects were influencing ones. In fact, most of the influencing defects were related to the structural distress group. The methodology confirmed that the erosion void defect was a vital defect to consider as its influence power weight was 8.8%. Besides, roots defect had the highest influence power weight (7.8%)

under the operational group. However, the least defect contributing to the grade's calculation was protruding services. The integrated model was implemented on the Royal Gardens' sewer network located in Edmonton, Canada. It was deduced that none of the pipelines were in critical condition. However, the majority of the assets were in Fair and Poor conditions (92%). These pipelines, if not efficiently rehabilitated, could degrade to critical states due to aging. The performance of the model was tested and validated with the actual data. The inclusion of the erosion void defect was reflected in the low TPR values and the calculated errors. Yet, the average accuracy and TNR percentages were 74% and 79%, respectively.

Based on the validity and accuracy percentages, the presented model will enhance the evaluation of sewer pipelines for better rehabilitation decisions. As a result, defective sewer pipelines are lessened, dramatic collapses are avoided, and the exfiltration of sewage is reduced. Nevertheless, this model can be further improved by checking the consistency of the responses of the participants to ensure reliable input data in the average influence matrix calculation. It is also recommended to validate and test the developed model on a bigger dataset to conclude robust outcomes. This model offers decision-makers the ability to modify the grading schemes in accordance to their available inspection technologies, without affecting the core elements of the model (influence power weights). The model is also scalable in case municipalities are interested in adding additional defects. A similar methodology is followed concerning the QFD-DEMATEL and grading scale calculation. However, questionnaires shall be designed and distributed to experts to collect the influence power of the added defects.

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7 Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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