Criticality Model to Prioritize Pipeline Rehabilitation Decisions

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ABSTRACT

Sewer networks are comprised of a huge maze of underground pipelines. They are designed and laid to transfer sewage medium to treatment plants or disposal areas. However, their conditions are subject to deterioration owing to ageing. The American Society of Civil Engineers (ASCE) (2017) claimed that the sewer infrastructure grade is D+. Inspection, assessment and effective decisions are required to enhance their performance through their service life. There are several inspection methods and assessment models that can evaluate the condition of the pipelines. When evaluating the global network, the city or municipality will end up having thousands of pipeline conditions. Therefore, they confront obstacles in deciding which pipelines to tackle first. The objective of this study is to design a criticality model that is based on multiple factors that could affect the criticality of one pipeline to another. The study evaluates the weights for the environmental, economic and public factors as well as their sub-factors by using the Analytic Network Process (ANP). The results concluded that the most important factor is the economic factor. The criticality model is implemented on an actual case study brought from the city of Edmonton, Canada. Based on the results, 20% of the pipelines are of low criticality; 70% are of medium criticality and 10% are of high criticality. This study is expected to enhance the prioritization of the pipelines in the network for efficient future decisions.

INTRODUCTION

Sewer assets have been a major concern in North America as their conditions are deteriorating and many are exceeding their designed service life (Kaddoura et al. 2017). According to the American Society of Civil Engineers (ASCE) (2017), the overall wastewater collection system condition is grade D+; among the lowest infrastructure grades in the United States (US). Not only but also, the Canadian Infrastructure Report Card (CIRC) (2016) stated that more than half of the linear wastewater assets' physical conditions ranged between very poor to good states with a total replacement value of $47-billion. Therefore, effective maintenance, rehabilitation and replacement (MR&R) plans are required. These plans shall enhance the performance of each asset and therefore, the overall of the sewer network. Based on the reinforcing loop shown in Figure 1, when the overall sewer system performance is excellent, the rehabilitation requirements will be less and hence the rehabilitation costs are less. Consequently, more funds are available to construct newer sewer assets, if needed. Moreover, the overall network performance will be enhanced.

Sewer pipelines are firstly inspected to understand the state of the asset. In spite of the availability of some sophisticated inspection techniques (Kaddoura 2015), the Closed Circuit Television (CCTV) method is the most commonly used one. The method is conducted through a camera that records the inner surface of the pipeline. Subsequently, the recorded video is interpreted through defects and severities, if any. Based on the observed distress, an overall grade is calculated, which explains the overall condition of the pipeline following a specific standard. The Water Research center (WRc) in the United Kingdom standardized an evaluation method for sewer pipelines (Malik et al. 1997) that is based on defect groups and scores. Due to the high number of sewer pipelines in any urban city, rehabilitating all deficient pipelines could be a difficult task given restricted budgets (Salman and Salem 2011). Therefore, a prioritization tool is required to point out the critical sewer pipelines. As a result, the main objective of this paper is to calculate the criticality of sewer pipelines considering environmental, economic and public factors and sub-factors. The criticality index, ranging from 1 to 5, is calculated after aggregating all factors and sub-factors through weights found from the Analytic Network Process (ANP). Therefore, this study is aiming to enhance the methodology in prioritizing sewer rehabilitation plans by considering several factors and sub-factors and studying the interdependencies among them.

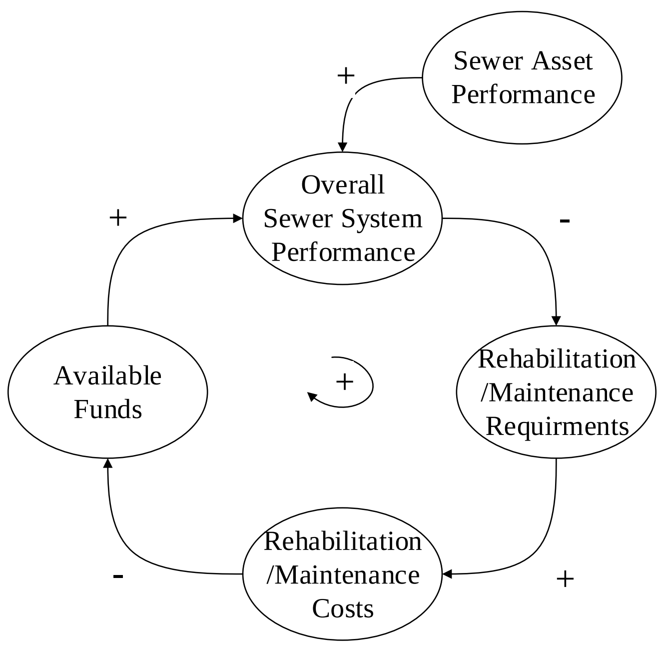

Figure 1. Reinforcing Loop

BACKGROUND

Sewer systems are one of the essential infrastructure elements in any urban city as defective pipelines may lead to harmful human health impacts (Gallay et al. 2006 and Bradbury et al. 2013). Sewage material may exfiltrate through a damaged or collapsed pipelines and contaminate drinking water sources and the surrounding soils. As a result, wastewater systems are considered as a critical infrastructure.

Criticality in infrastructure has attracted several researchers in construction management. Theoharidou et al. (2010) defined criticality as "the contribution level of the infrastructure to the society in maintaining a minimum quality level of vital social functions, health, safety, security, economic or social well-being of people". Besides, some English dictionaries expressed the criticality as "the quality, state, or degree of being of the highest importance." Besides Theoharidou et al. (2010), Miles et al. (2007) expressed the criticality as the consequence of failure of the asset. In fact, Syachrani et al. (2013) defined critical assets as assets with a high probability of failure and high consequences if they do fail. Moreover, it is of great importance to study the criticality of one asset to another to conclude efficient rehabilitation decisions. This can be accomplished by so-called, criticality assessment, which is the process of assessing the criticality level of an asset (Theoharidou et al. 2010) considering its consequence of failure.

In assessing the criticality of infrastructure components, several works have been conducted to serve certain objectives. In this context, Miles et al. (2007) proposed a pipeline rehabilitation priorities decisions by considering the condition of the pipelines and their criticality criteria. The rehabilitation proprieties were set based on available information related to the probability of failure and the consequence of failure criteria that was weighted by some experts. The authors identified certain factors that could influence the probability of the failure and the consequence of failure. Under the condition category, the authors subdivided the capacity, structural and maintenance into several sub-factors. However, the criticality group was subdivided into four different sub-groups: environmental impact, size, transportation impact and ease of repair/reliability; each sub-group was decomposed of several factors. The authors assigned higher levels to a facility that was more critical compared to the others. The criticality rating was calculated by adopting the assigned levels to each criticality factor. However, the condition rating was computed based on the levels assigned to each condition factor and their relative importance weights. After all, the authors concluded their decisions based on a 5 x 5 matrix that was constructed based on the condition and criticality parameters. Critical assets that required immediate actions topped their rehabilitation actions' list.

In addition, Salman et al. (2011) defined the criticality as the consequence of failure as they proposed a risk-based model to prioritize the wastewater rehabilitation decisions. The authors acquired weighted scoring system to determine a numerical consequence of failure value for each pipe section. The risk level was computed by aggregating the consequence of failure with the probability of failure. They adopted three different models in their computations, namely: the multiplication of probability and consequence of failure, risk matrices and fuzzy inference system. Number of factors were identified that could affect both the criticality such as the proximity to the nearest building, depth, size, number of complaints, roadway type, location, etc.

Syachrani et al. (2013) proposed a criticality based assessment model for sewer pipeline assets. They modelled their approach based on risk assessment that was comprised of probability of failure and consequence of failure. They introduced a new method using the "real age" of a pipe in estimating the probability of failure. However, the consequence of failure was estimated based on the semi-parametric survival analysis which were assessed from information of a Delphi workshop. Subsequently, the risk level was calculated by the multiplication factor of the probability of failure and the weighted consequence of failure.

In addition, Baah et al. (2015) proposed a risk-based model to prioritize the future inspection of uninspected wastewater pipelines to the natural and built environment. The authors computed the probability of failure of the asset based on estimating the grade of the sewer pipeline using deterioration model. However, the consequence of failure for each pipeline was determined according to a weighted-sum scoring matrix system. Several factors were identified to calculate the consequence of failure such as: the roadway type, pipe size, depth, proximity to building, proximity to hospitals, proximity to rivers, etc. The risk of failure was then computed using the risk matrix system.

Additionally, Hahn et al. (2002) proposed an expert-based system after utilizing the Bayesian belief network model. The authors interviewed experts to understand the process of sewer pipeline failure along with their consequences. The consequences of failure were then grouped into socio-economic and reconstruction impact. The socio economic included human health, environmental, commerce and traffic; while the latter considered tunneling, resurfacing costs and access redundancy.

Despite the enormous number studies related to criticality/risk assessment in sewer pipelines, some researches were limited to few number of factors and sub-factors that could impact the criticality assessment. Besides, some of the reviewed literature did not incorporate the interdependency that exists between the factors when computing weights of the consequence of failure factors.

As a result, this research is aiming to incorporate factors that were not considered previously and consider the interdependency when calculating the weights of the factors through the application of the ANP method.

RESEARCH METHODOLOGY

Several researchers have expressed the criticality of an asset as its consequence of failure. As a result, the methodology was based on collecting factors that affect the criticality of one pipeline to another. Several environmental, economic and public factors were considered in the assessment as per Figure 2. In fact, each of them had several sub-factors. The criticality index of each asset is computed through the weighted sum. To calculate the weights of each factor, a questionnaire was designed and distributed to experts in the field. Later, the responses are analyzed and ANP method is deployed to find out the local weights. These weights are then used to aggregate all criticality values to supply a criticality index between 1 to 5; where 1 corresponds to least critical pipeline and 5 is extreme critical pipeline.

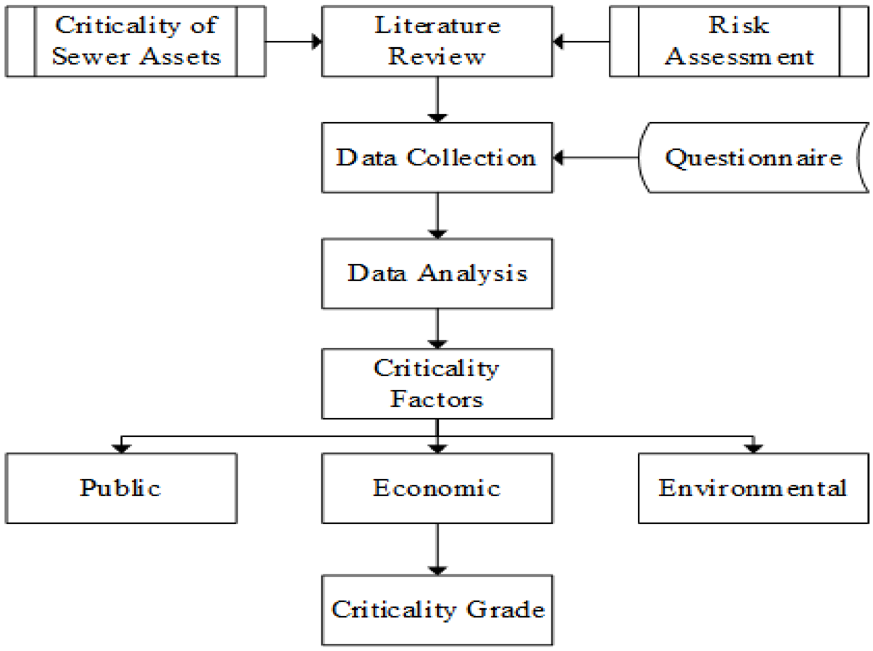

Figure 2. Research Methodology

CRITICALITY FACTORS/SUBFACTORS

Criticality is assessed based on three main factors, which are environmental, economic and public as per Figure 3. Environmental factor is measured based on soil type, flow conveyed, and proximity to surface water. The economic factor is assessed according to the depth, diameter, water table presence, length and accessibility for rehabilitation. The public factor is computed by incorporating the population density, road type, land use, length of pipeline, accessibility, diameter, and depth.

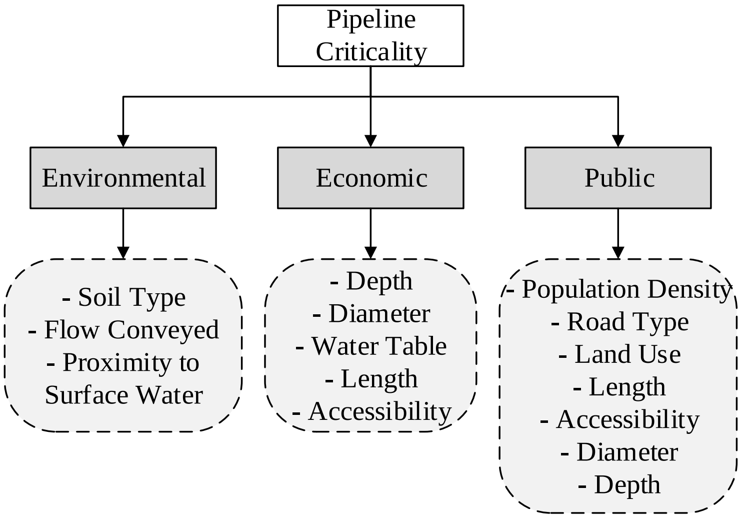

Figure 3. Criticality Factors/Sub-factors

Soil Type

Soil form an envelope to the asset as it surrounds pipelines all around. Soil types range between fine aggregate to coarse aggregate. The finer the particle, the easier is the exfiltration and vice versa. Therefore, the most critical case is when particles are the finest as they will expedite the exfiltration flow to the surroundings. The soil type are categorized according to Table 1. Gravel soil type is Excellent when compared to finer soils like clay.

Flow Conveyed

The flow conveyed is determined according to the location of the pipeline from the upstream. The upstream asset in not as critical as the downstream asset given similar conditions. Any failure in the downstream asset will exfiltrate more sewer medium to the surrounding due to more flow transfer. Hence, it will increase the chance of having environmental impacts once failed. The determination of the flow conveyed factor is according to the flow direction in the network and the accumulation of the flow. The accumulation of the flow is based on the contribution of each pipeline. The factor of each pipeline is determined according to the maximum accumulated flow. Therefore, the accumulation flow factor is determined according to Equation 1.

$$Accumalation\ Flow\ Factor\ = \frac{flow\ conveyed}{Maximum\ Accumaltion} \quad [1]$$

As an illustration, the simple network in Figure 4 is comprised of five pipelines and three manholes. Each pipeline will contribute to the flow by a factor of 1. Therefore, the accumulation flow factor may differ from one asset to another. For example, P1 will have a factor of 1 to the network. Yet, P2 will have its own flow and the flow from P1. For example, considering equation 1, the accumulated flow factor of P2 is (2/5).

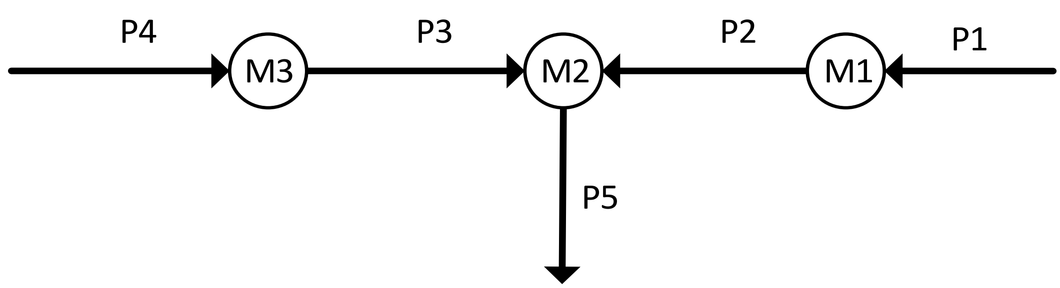

Figure 4. Sample of Sewer Network

Accordingly, the final downstream asset will transfer all the flow received from all other assets in the network, it will be the most critical asset. Any failure in this asset, will have the highest exfiltration flow compared to other assets and hence will impact the surrounding environment. Based on this concept, five different ranges have been prepared as per Table 1.

Proximity to Surface Water

Any sewer exfiltration will have a negative impact on the surrounding environment. City inspectors have high chances of locating sewer overflows on land than in surface water. Sewer pipeline could cause severe consequences for the surface water as it may impact the water quality and hence the water habitats. Therefore, the nearer the asset to surface water, the more critical is the situation. The criticality is determined based on the nearest distance of the sewer asset to the surrounding surface water as shown in Table 1.

Depth

Deeper pipelines require extensive excavation for replacements. As a result, it costs higher than a shallower pipeline. Besides, to prevent the soil from caving in, the bank angle shall be considered. Therefore, more construction areas are used. Hence, it will increase the public disruption. Accordingly, these two criteria will affect the economic and public factors in the calculation of criticality as per Table 1.

Diameter

The decision on a pipeline diameter size is based on the designed flow for a specific area. Bigger diameters cost more than smaller ones and require more space for replacement. Therefore, they are more critical than smaller ones as per Table 1.

Water Table

Sewer pipelines are buried underground; their laying process involves, trenching, excavation, piling, backfilling, etc. In fact, sometimes, the underground water table may present and can impact the installation process. Before the assets are laid, dewatering process is required to ensure that the bottom of the excavation is in a proper state for the asset to be installed. In general, deeper sewer lines involves dewatering process (Swamee 2001). As a result, this will add to the cost and require additional financial resources. The criticality assessment corresponding to this factor is based on two criteria as shown in Table 1. Pipelines that are above the ground water table are less critical than the ones below it.

Length

The common practice to order pipelines is according to its length. As a result, a longer pipeline will cost more than a shorter one. Besides, a longer pipeline requires more construction space than shorter pipelines, which will impact the public comfort. Based on this explanation, the criticality is displayed in Table 1.

Accessibility

Inaccessible places are like confined areas where large construction equipment cannot enter the site. Therefore, minimal access to a failed asset requires additional resources for repair tasks. Also, additional time will be required to repair the damage. Hence, it will add to the cost of the project. According to the US Environmental Protection Agency (EPA) (2015), inaccessible areas could lead to increased impacts to the community. The agency also stated that longer repairs contribute to longer disruption. As a result, Table 1 accommodates the criticality of this factor based on three criticalities (accessible, moderate and inaccessible). The more the area is inaccessible, the more critical is the situation.

Population Density

The higher is the population density, the more critical is the situation. When sewer assets fail, some sewer medium will be exposed to the public; therefore, it could impact the public health. The higher number of people residing in an area of a failed sewer asset, the higher potential exposure to sewer medium and the higher is the health impact.

Road Type

Sewer assets could be laid in different locations; they could be found beneath roads in urban cities. As a result, any failure in the asset could disturb the public as the travel time will increase. Hence, municipalities need to control road traffic by flagging to facilitate construction. With the efforts, some sections of the road will be closed due to rehabilitation tasks. The most critical situation is when an asset fails in a high capacity roads as per as shown in Table 1. In this research, roads are categorized as local, collector, arterial, highway and freeway.

Land Use

The criticality of a failed sewer asset differ based on land it is laid in. For example, in an abandoned space, the criticality of a failed sewer asset is lower when it is compared to an institutional place. Therefore, different criteria has been set to consider this type of public factor as shown in Table 1.

Table 1. Criticality Sub-factors Criticality Values (Non-critical = 1 to Extreme Critical =5)

Factor	Type	Unit	Criticality Value
Soil Type	Gravel		1
	Course Sand		2
	Fine Sand		3
	Fine Sand and Silt		4
	Clay		5
Flow Conveyed	<0.2		1
	0.2- <0.4		2
	0.4- <0.6		3
	0.6- <0.8		4
	0.8-1		5
Proximity to Surface Water	> = 450 m		1
	450 – 215	m	2
	215 – 120	m	3
	120 – 45	m	4
	< = 45	m	5
Pipeline Depth	< = 2	m	1
	2 to 3	m	2
	<3 to 3.5	m	3
	<3.5 to 4	m	4
	>4	m	5
Pipeline Diameter	< = 300	mm	1

	300 to 450	mm	2
	<450 to 750	mm	3
	<750 to 1200	mm	4
	>1200	mm	5
Water Table	Asset Above Water table		1
	Asset Below Water table		5
Pipeline Length	<30	m	1
	30-75	m	2
	<75-120	m	3
	<120-150	m	4
	>150	m	5
Accessibility	Accessible		1
	Moderate Accessibility		3
	Inaccessible		5
Road Type	Local		1
	Collector		2
	Arterial		3
	Highways		4
	Freeway		5
Land Use	Abandoned Space		1
	Agriculture		2
	Residential/Park		3
	Industrial		4
	Institutional and Health Centre		5

CRITICALITY GRADE

In this research, the criticality grade ranges between 1 and 5, where 1 represent a non-critical asset while 5 represents an extremely critical assets. The factors and sub-factors' weights are calculated based on the ANP method. Therefore, each will have a relative importance weight. All factors involved in the model will be aggregated to conclude a criticality grade. In order to find the pipeline criticality grade, one can use Equation 2

$$CRI_{Pi} = \sum_{n=1} W_{ij} \left(\sum_{n=1} w_{ijk} * x_{ijk}\right) \qquad [2]$$

Where

- *W* is the relative importance weight of factor *j*
- *w* is the relative importance weight of sub-factor *k* in factor *j*
- *x* is the criticality value in sub-factor *k* under factor *j* for asset *i*.

Therefore, a grade from 1 to 5 will be found. This grade can be interpreted according to Table 2. The higher the grade, the more critical is the asset on the environment, public and economy and vice versa.

Table 2. Criticality Grade Description

Overall Grade	Criticality	Description
1.00 to <1.50	Non Critical	If failed, the asset is not critical to the environment, economic and public
1.50 to < 2.00	Low	If failed, the asset has low criticality to the environment, economic and public
2.00 to < 3.00	Medium	Moderate criticality to the environment, economic and public
3.00 to < 4.00	High	High criticality to the environment, economic and public
4.00 to 5.00	Extreme	Asset is of extreme criticality if failed

MODEL IMPLEMENTATION

The preliminary weights calculation has been completed for one questionnaire by utilizing the ANP method. The ANP method supplied the weights of the factors and subfactors considered in this study. According to Table 3, the expert considered the economic factors to be more important than the other two main factors. In addition, the pipeline geometry is a major concern for criticality measures due to the constraint financial resources.

Table 3. Preliminary Criticality Weights

Factors	Weights	Subfactors	Local Weights	Global Weights
1. Environmental	22%	1.1 Soil type	32%	7.1%
		1.2 Flow Conveyed	33%	7.3%
		1.3 Proximity to Surface Water	34%	7.5%
2. Economic	51%	2.1 Depth	30%	15.5%
		2.2 Diameter	20%	10.3%
		2.3 Water Table	5%	2.8%
		2.4 Length	24%	12.4%
		2.5 Accessibility	20%	10.4%
3. Public	27%	3.1 Population Density	32%	8.6%
		3.2 Road Type	29%	7.8%

3.3 Diameter	10%	2.7%
3.4 Length	10%	2.7%
3.5 Depth	15%	4.0%
3.6 Accessibility	2%	0.5%
3.7 Land Use	2%	0.5%

The global weights are used to compute the criticality indexes for ten sewer pipelines located in the Royal Gardens neighborhood in Edmonton, Canada. Table 4 displays the criticality values for the pipelines considered after reviewing each pipeline's data. According to the results, 20% of the pipelines are of a low criticality. Yet, the 70% of the pipelines are of medium criticality and only one pipeline's criticality is high. In case similar failure occurs for these ten pipelines, pipeline 2 will be rehabilitated first.

Table 4. Preliminary Criticality Results

Factor	**1**			**2**					**3**							
Subfactor	**1.1**	**1.2**	**1.3**	**2.1**	**2.2**	**2.3**	**2.4**	**2.5**	**3.1**	**3.2**	**3.3**	**3.4**	**3.5**	**3.6**	**3.7**	**Criticality**
Weight	**0.071**	**0.073**	**0.075**	**0.155**	**0.103**	**0.028**	**0.124**	**0.104**	**0.086**	**0.078**	**0.027**	**0.027**	**0.040**	**0.005**	**0.005**	
Pipe #																
1	3	1	1	4	1	1	3	1	1	1	1	3	4	1	3	2.04
2	2	1	1	5	2	1	3	5	5	1	2	3	5	5	3	3.07
3	3	1	1	3	1	5	2	1	1	1	1	2	3	1	3	1.81
4	3	1	1	5	1	1	2	1	1	1	1	2	5	1	3	2.08
5	3	1	1	5	1	1	1	1	1	1	1	1	5	1	3	1.93
6	2	3	1	5	2	1	1	3	5	3	2	1	5	3	5	2.87
7	3	1	1	5	1	1	2	3	5	3	1	2	5	3	5	2.81
8	2	3	1	5	2	1	3	3	1	4	2	3	5	3	3	2.89
9	2	1	1	5	2	1	4	3	1	4	2	4	5	3	3	2.90
10	3	1	1	3	1	5	3	5	5	1	1	3	3	5	3	2.74

CONCLUSIONS

Regular inspection and proactive maintenance are required to ensure well-performing sewer pipelines. Due to scarcity of resources, municipalities confront obstacles in prioritizing their interventions, which could be solved through a criticality model. This research suggested a criticality assessment for sewer pipelines based on three main factors: environmental, economic and public, in which each had several sub-factors. The criticality grade is calculated based on the weighted sum that ranged between 1 and 5, where 1 described a non-critical pipeline, whereas, 5 expressed an extremely critical pipeline. The ANP model was implemented on one questionnaire and among the main factors, the most important one was the economic factors. In addition, the suggested model was implemented on a real case study. The computations revealed that 20% of the pipelines have low criticalities; 70% have medium criticalities and only one pipeline had high criticality. This research is expected to enhance sewer rehabilitation prioritization by using the suggested model as it incorporated several factors that were neglected previously and studied their interdependency.

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