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Assessment Framework for the Maintainability of Sewer Pipeline Systems

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Abstract: The maintainability of sewer infrastructure systems is vital for public health, environmental protection, and the overall well-being of communities. However, maintenance and repair activities for sewer pipelines are often constrained, leading to challenges in effectively managing such infrastructures. To address these challenges, this study assessed the maintainability of sewer pipelines. A total of 15 defects were identified and categorized into structural, hydraulic, and quality defects after a comprehensive literature review was conducted and sewer pipeline experts were interviewed. Each failure caused by these defects was categorized as a pipe collapse associated with structural defects, sewer system overflow (SSO), odor, and groundwater contamination associated with quality defects. Apart from assessing the defects, the study identified potential solutions. After that, the obtained data were analyzed to determine the relative significance of each probability identified and its impact on four parameters, economic, social, environmental, and detection difficulty, using the relative importance index (RII), while the risk value index (RI) was applied to prioritize the defects. Furthermore, a data reliability assessment was utilized to evaluate internal consistency. The findings indicate that the probability of joint defects in the structural category caused by weaknesses in welded joints due to the misalignment of plastic pipes or joints, especially spigot and socket joints for rigid pipes, was the highest (RII = 0.733). Additionally, the ranking showed that the dumping of FOG had the highest priority, with an RI value of 0.535. This study offers a comprehensive maintainability framework that can be utilized by agencies assessing their current sewer infrastructure systems, in particular Arab Gulf countries including Saudi Arabia, which is the subject of this study.

Keywords: maintainability; sewer pipelines; defect causes; relative importance index; risk value index

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1. Introduction

The increase in human, industrial, and commercial activities in recent years can negatively affect public health and environmental systems. In the same context, rainwater and sewage drainage systems are essential in preventing dangers due to water pollution, which damages public health, living organisms, and the environment. Therefore, highly efficient drainage systems have become necessary in light of the urban renaissance of cities and urban areas. A wastewater collection system accumulates domestic, commercial, and industrial wastewater and then transports it to a wastewater treatment plant before it is discharged into the surrounding environment [1]. Untreated wastewater can contain hazardous substances which are detrimental to human health and the natural environment; therefore, wastewater collection systems are essential for protecting the environment and the public's health [1].

The wastewater collection system is a vital component of infrastructure because it plays a significant role in decreasing the dangers of flooding and the contamination of water supplies. For instance, if heavy rainfall exceeds a system's actual capacity, the pipes will

face an overflow. Consequently, untreated wastewater may overflow and be discharged from the sewer system into the surrounding environment [2]. This typically occurs due to defects in the sewer pipeline, such as system design insufficiencies, pipe collapse, blockages, or excessive flow beyond the pipe's capacity [3]. According to the Environmental Protection Agency of the United States, there are around 23,000 to 750,000 cases of sanitary sewer overflow each year, releasing 11.4 to 37.9 million cubic meters of untreated wastewater into the environment [4].

Saudi Arabia has a thousand miles of sewer pipelines, and instances of sanitary sewer overflow occur frequently. In addition to the damage caused to the environment and society, instances of this nature also increase the burdens and costs associated with the operation and maintenance of sewer pipes. In the KSA, the vision of the Kingdom of Saudi Arabia for 2030 encompasses enormous infrastructure projects worth billions of SAR, including projects involving sewer pipelines.

Sewer pipeline maintenance is an unseen but very costly component of infrastructure [5]. It is common knowledge that dysfunction is more likely to occur in sewer networks that have any of the following characteristics: longitudinal slopes lower than the minimum allowed; small minimum pipe profiles; poorly constructed and performing joints and longitudinal slopes; large numbers of cracks, deformations, and fractures due to poor installation; and undisciplined users who dump substances and foreign bodies into the sewer [6]. The various defects that can occur in sewer pipes were captured via closed circuit television (CCTV) and are illustrated in Figure 1.

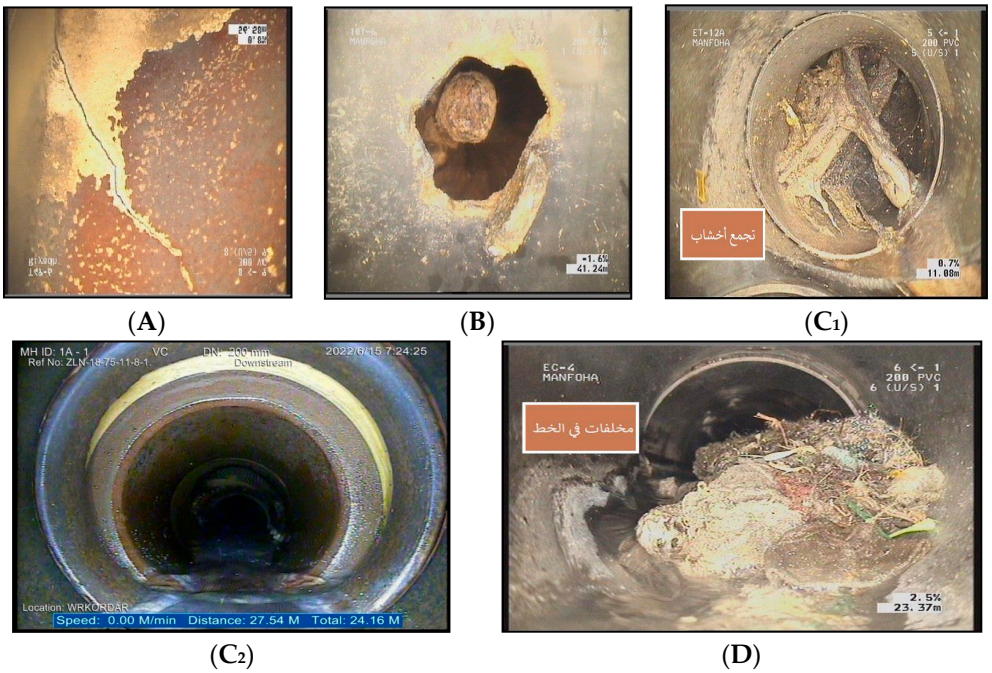


Figure 1. (**A**) A crack; (**B**) a broken pipe; (**C1**,**C2**) an undesirable substance; (**D**) root intrusion.

2. Literature Review

Previous studies were conducted to identify significant sewer pipe defects and their causes and failure classifications, using different approaches such as a fault tree analysis (FTA); cause-and-effect diagrams; a failure mode, effects, and criticality analysis (FMECA); and total quality management (TQM) [7–9]. In the case of pipe defects, many researchers [10–13] concluded that the major defects are pipes breaking, deformation, wall fractures, misalignment, displaced sewer joints, sediment accumulation, FOG clogging, solidification, hydrogen sulfide (H2S) emissions, root intrusion, soil intrusion, infiltration, detachment, lining wrinkles, lining collapse, and joint damage. In addition to these defects, damage to sewage works, including facility tampering, vandalism, and improper use due to

either the presence of illegal discharges or the introduction of foreign objects such as paper, rags, or construction materials into the sewage pipelines, can be caused by unauthorized or unidentified third parties [14].

Furthermore, several studies classified these defects into different categories [15–19]. For example, Ana et al. (2010) and Chughtai et al. (2007a) classified the defects into physical, environmental, operational, and construction defects [15,16]. Similarly, Chughtai et al. (2007b) clustered pipe defects into hydraulic and non-hydraulic defects, and both types potentially influence operational conditions [17]. Another research study [18] pointed out that the defects' failures can be broken down into four categories: operational, strength, containment, and capacity. Tizmaghz et al. (2022) proposed three top-level categories of failure, physical failure, hydraulic failure, and quality failure, and each category was broken down into subcategories [19]. For instance, failures occur when there are releases into the sewage, internal sewage processes, exfiltration, or overflows which lead to contamination or odors inside or outside the system to the extent that immediate remedial action is required [19]. Likewise, Yanfen et al. (2022) undertook a comprehensive survey to investigate previous studies on common defects in sewer pipes, resulting in the identification of 12 specific defects that mainly contribute to the deterioration of sewage pipe conditions. The primary emphasis of the study was placed on structural defects rather than operational defects. The survey revealed that structural defects, such as cracks, deformations, and joint displacements, were found to be the major contributors to the deterioration of sewage pipe conditions. These defects pose significant risks to the overall integrity and functionality of sewer systems. Additionally, operational defects like infiltration and deposits were also considered but were not the primary focus of the study [20].

Pipe defects can be attributed to numerous factors. These contributing elements, as reported in previous studies, include excessive loading, poor pipe bedding, pipe abrasion, pipe corrosion, external hydrostatic loads, third-party damages, soil disturbance, bedding configuration, improper installation, improper materials, weaknesses in welded joints, small pipe slopes, rainwater ingresses, illegal discharge, poor sewer maintenance practices, improper constructed joints, improper bedding, damage during compaction, improper pipe positioning, insufficient system hydraulics, flat grades, flow disturbance and the exfiltration of wastewater in the pipe or manhole [21–33]. Table 1 summarizes the findings from previous studies. It categorizes the types of defects, their subcategories, and contributing factors, as identified in the literature.

Table 1. Sewer pipe failures, defects, and causes.

Failure	Defect Category	Defect	References	Contributing Factors
Pipe collapse	Structural defects	D1—the cracking and fracture of rigid pipes	[10–12]	Excessive loading and poor pipe bedding can cause pipe cracks and fractures; Steep slopes with high velocities generate H_2S gas, which accelerates abrasion and corrosion and leads to cracks.
		D2—the deformation of flexible pipes	[10–13,22]	Excessive external loadings, thermal soil loads, or other mechanical causes (for example, a point load from a boulder in the backfill or bedding, or root action).
		D3—pipe breaks	[10–14,19]	Third-party damage (tampering and damage to sewage works by private and/or unknown persons).
		D4—failing utilities	[14,20]	Failed utilities located in the vicinity of the wastewater pipeline can result in soil disturbances and possible changes in bedding configuration, ultimately leading to wastewater pipe failure.

Table 1. *Cont.*

Failure	Defect Category	Defect	References	Contributing Factors
		D5—defective lining	[12,13,23]	Improper installation and material.
		D6—joint defects	[10,12,13]	Weaknesses in welded joints due to the misalignment of plastic pipes or joints, especially the spigot and socket joints of rigid pipes.
Sewer system overflow (SSO)	Hydraulic defects	D7—sediment accumulation	[10,11,13,25–27]	Small pipe slopes that reduce flow velocity; A high level of groundwater infiltrating through structural defects, carrying soil particles into the pipe.
		D8—inflow	[14,28]	Rainwater ingress through structural defects, separated joints, opened joints or manholes which increases flow during rainfall events.
		D9—the dumping of fat, oil, and grease (FOG)	[10,14]	Illegal discharge from restaurants.
		D10—the dumping of foreign objects (paper, rags, construction material, etc.)	[14]	Improper handling.
		D11—root intrusion	[11,12,29]	The improper choice of joints; Wrongly constructed joints; Structural pipe defects; Sewer maintenance practices (improper root removal).
		D12—the ingress of soil	[11,29]	Wrongly constructed connections/joints; Improper bedding/foundation; Damage during refilling/compaction; Improper choices of pipe and joint type/material; Improper pipe positioning
		D13—infiltration due to elevated groundwater	[11–14,25–27,30,31]	The infiltration of a high level of groundwater, structural defects, separated joints, and opened joints or manholes.
Odor and groundwater contamination	Quality defects	D14—the production and release of H_2S	[10,12,19,20,32]	The build-up of solids, poor system hydraulics, and a flat grade; Flow disturbance due to a large difference in the level between the inlet pipe and the outlet pipe in the manhole; The exfiltration of wastewater due to defects in pipes or manholes.

From the literature, it is clear that no previous research was conducted on sewer system defects and their causes in Saudi Arabia. Also, previous studies made little effort to explore whether maintenance is feasible in these systems. Consequently, a comprehensive study is needed to assess the maintainability of the sewer pipelines in the Kingdom of Saudi Arabia. A detailed investigation of the planning, design, implementation, operation and maintenance, including defects and failures, of sewer lines was carried out through a maintainability framework. Potential solutions for mitigating these defects are also addressed in this study. The outcomes of this research could help reduce the frequency of failures and malfunctions, thereby improving the maintainability of sewer systems. Most of these systems consist of gravity-based sewer pipelines that rely on slope for flow

transmission. This study specifically focuses on enhancing the maintainability of such pipelines in Saudi Arabia.

The paper aims to bridge several critical knowledge gaps in the field of sewer infrastructure maintainability assessment. Firstly, it addresses the dearth of research conducted in the unique context of Saudi Arabia, emphasizing the need for region-specific insights due to varying environmental conditions and operational challenges. While existing methodologies like fault tree analyses and cause-and-effect diagrams are valuable, they may not consider the specific challenges encountered in the Kingdom of Saudi Arabia. This paper seeks to rectify this gap by offering a more tailored perspective that takes into account the region's distinct requirements and issues.

Moreover, the paper adopts a more comprehensive approach compared to many existing methodologies. It delves into all the phases of a sewer pipeline's lifecycle, from initial planning and design to operational aspects and maintenance. This holistic perspective provides a more integrated view of maintainability, offering a practical guide for policymakers, engineers, and stakeholders involved in sewer infrastructure management. By addressing not only defect identification but also the feasibility of maintenance, this research complements existing methods and offers a more complete framework for enhancing the maintainability of sewer systems.

3. Research Methodology

The research methodology adopted in this study involves a combined quantitative and qualitative approach. The framework of this mixed-methods approach is illustrated in Figure 2. With the comprehensive nature of quantitative data complemented by the detailed insights drawn from a qualitative analysis, this approach aims to generate an in-depth understanding of the relevant pipe issues that impact maintainability. Moreover, it seeks to support the validity and reliability of the findings, thereby enriching the overall quality and scope of this study.

Specifically, this study was conducted using the following steps: firstly, the authors carried out a comprehensive literature review to investigate the most frequent defects and their possible contributing factors while taking into account economical (P1), environmental (P2), social (P3), and detection difficulty (P4) parameters that influence the process of deterioration in collection systems for sewer pipelines. Secondly, interviews were conducted with experts with rich experience in operating and maintaining sewer pipelines in Saudi Arabia to validate the results of the literature review. To qualify as an expert capable of providing insightful opinions, one must possess at least 10 years of relevant experience, in line with [34,35]. Four experts with more than ten years of experience were interviewed for this purpose, and their qualifications are reported in Table 2.

Fourteen sewer pipeline issues and their causes were identified from the literature review, and the experts were asked to answer questions provided below.

Q1. Are the defects and causes in this study reflective?

The experts were asked to answer YES or NO and to provide any other defects or causes they had identified.

Q2. What are the possible contributing factors to these defects?

Table 3 presents a compilation of defects and their contributing factors which were initially gathered from a comprehensive literature review and subsequently verified and refined by the experts. In Table 3, the text highlighted in bold denotes the additional insights contributed by the experts.

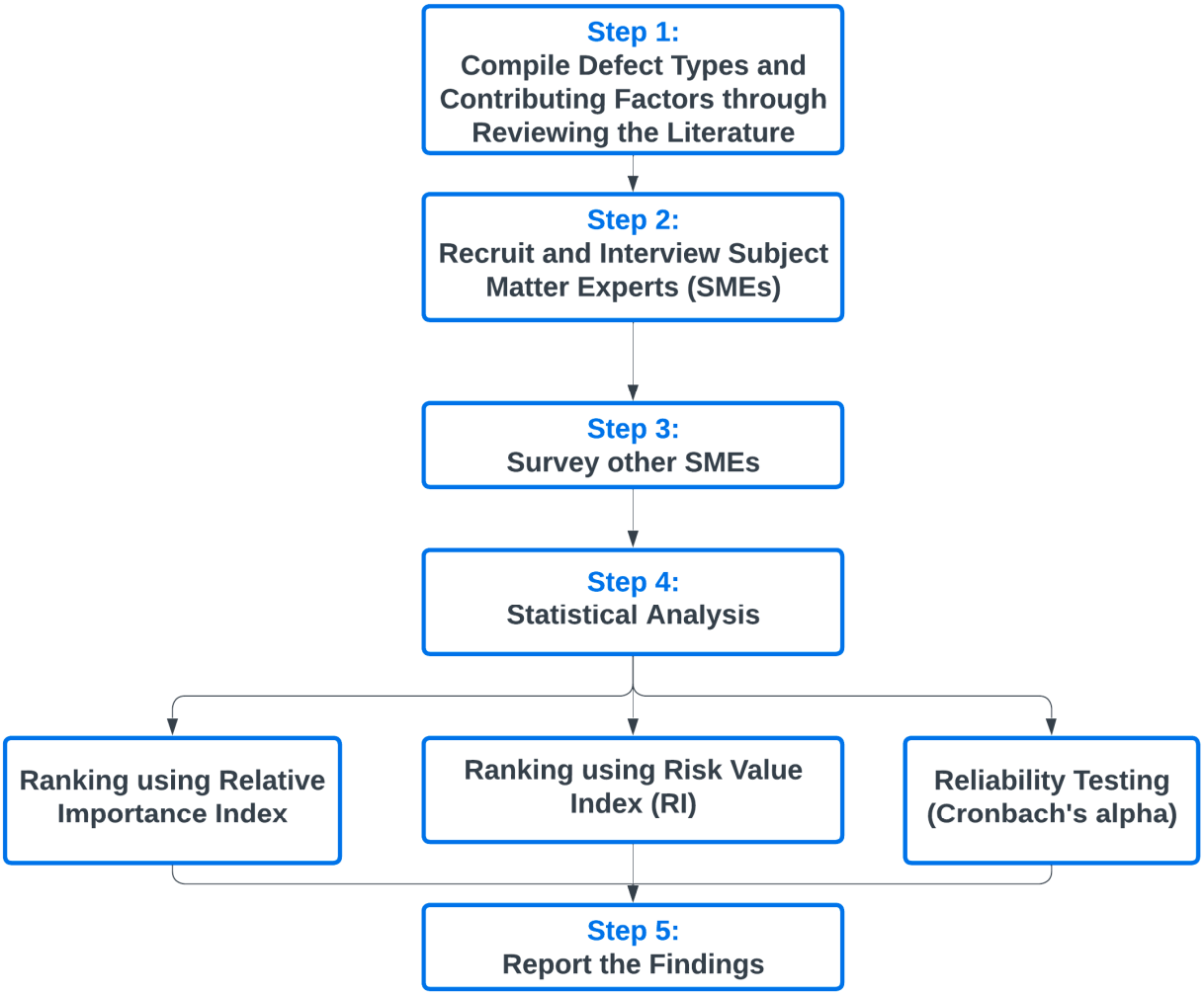


Figure 2. Methodology framework.

Table 2. Profiles of the experts based on their degree, organization type, years of experience, and the locations of their past and current employment.

Expert	Degree	Organization Type	Role	Years of Experience	Locations of Past and Current Employment
EX1	Bachelor of Civil Engineering and Master of Business Administration	Governmental	Sewer network operation and senior maintenance manager	25	Saudi Arabia
EX2	Bachelor of Mechanical Engineering	Governmental	Sewer network maintenance manager	21	Saudi Arabia
EX3	Bachelor of Civil Engineering	Consultant	Sewer network operation specialist	14	Past: Egypt; Current: Saudi Arabia
EX4	Bachelor of Civil Engineering	Consultant	Sewer network senior engineer	19	Past: Egypt and Oman; Current: Saudi Arabia

Table 3. Defects and contributing factors after a review by the experts (note: the emboldened lines signify items that were added by the experts).

Defects' Category	Defect	Defect Code	Contributing Factor	Contributing Factor Code
Structural defects	The cracking and fracture of rigid pipes	D1	Excessive loading, along with poor pipe bedding and the use of inappropriate backfill soil containing stones and sharp material with no compaction, can cause pipe cracks and fractures.	C1
			Steep slopes with high velocities generate H_2S gas, which accelerates abrasion and corrosion, leading to cracking.	C2
	The deformation of flexible pipes	D2	Excessive external loading, thermal soil loads or other mechanical causes (for example, a point load from a boulder in the backfill or bedding, or root action).	C3
	Pipe breaks	D3	Third-party damage (tampering and damage to sewage works by private and/or unknown persons).	C4
	Failing utilities	D4	Failed utilities located in the vicinity of a wastewater pipeline can result in soil disturbances and possible changes in bedding configuration, ultimately leading to wastewater pipe failure.	C5
	Defective lining	D5	Improper installation and material.	C6
	Joint defects	D6	Weaknesses in welded joints due to the misalignment of plastic pipes or joints, especially the spigot and socket joints of rigid pipes.	C7
Hydraulic defects	Hydraulic overflow	D7	A small pipe diameter less than the flow capacity.	C8
	Sediment accumulation	D8	Small pipe slopes that reduce flow velocity.	C9
			A high groundwater level infiltrating through structural defects, carrying soil particles into the pipe.	C10
	Inflow	D9	Rainwater ingress through structural defects, separated joints, and opened joints or manholes, which increases flow during rainfall events.	C11
	The dumping of fat, oil, and grease (FOG)	D10	Illegal discharge from restaurants.	C12
	The dumping of foreign objects (paper, rags, construction material, etc.)	D11	Improper use.	C13
	Root intrusion	D12	The improper choice of joints.	C14
			Wrongly constructed joints.	C15
			Structural defects in pipes.	C16
			Sewer maintenance practices (improper root removal).	C17

Table 3. *Cont.*

Defects' Category	Defect	Defect Code	Contributing Factor	Contributing Factor Code
	Ingress of soil	D13	Wrongly constructed connections/joints.	C18
			Improper bedding/foundation.	C19
			Damaging during refilling/compaction.	C20
			Improper choices of pipe and joint type/material.	C21
			Improper pipe positioning.	C22
	Infiltration due to elevated groundwater	D14	The infiltration of a high level of groundwater leads to structural defects, separated joints, and opened joints or manholes.	C23
Quality defects	The production and release of H_2S	D15	Solid build-up, poor system hydraulics, and flat grades.	C24
			Flow disturbance due to a large difference in the level between the inlet pipe and the outlet pipe in the manhole.	C25
			The exfiltration of wastewater due to defects in the pipe or manhole.	C26
			A lack of/poor preventive maintenance of the routine flushing of a sewer system.	C27

A survey instrument was prepared to evaluate the 15 defects in terms of (1) their likelihood of occurrence, (2) impact, and (3) difficulty to detect. A five-point Likert scale was utilized to assess the likelihood as follows: five for "Always", four for "Frequently", three for "Sometimes", two for "Scarcely", and one for "Never". As for the impact, the five-point scale utilized was five for "Catastrophic", four for "Major", three for "Moderate", two for "Minor", and one for "Insignificant". Similarly, the five-point scale used to assess the detection difficulty was 5 for " Very difficult", 4 for " difficult", 3 for " Moderate", 2 for " Easy", and 1 for " Very easy". A total of 18 experts, each with prior experience in the various aspects of working with sewer lines ranging from design and implementation to operation and maintenance, filled out the survey.

After compiling the data, a statistical analysis was conducted to evaluate the survey. A descriptive statistics analysis was performed to determine the central tendency and variability of the result. The relative importance index (RII) was also calculated to determine the relative significance of each identified probability and impact. Although the weighted mean was provided, the RII was selected because it is simple for participants to understand. Aside from justifying the implications of rating the probabilities and impacts, the number of issues investigated made it efficient to use the RII [34,36]. According to Salleh et al. (2009), the relative importance index (RII) is a statistical method used to rank various causes [37]. The relative importance index (RII), which is used extensively in the literature for ranking and evaluating variables, is calculated using the formula presented in Equation (1):

$$RII = \frac{\sum W}{A \times N} \quad (1)$$

where W shows each participant's weighting, while A and N are, respectively, the maximum weight and the total number of participants.

Apart from the calculation of the RII, each defect's risk value (RI) was calculated. The RI was derived by multiplying the probabilities of occurrence and impacts determined by the experts' judgments, which yielded the RI, using Equation (2) [34].

$$RI = P \times I \quad (2)$$

where P is the probability and I is the impact of a defect.

Lastly, the reliability of the results was evaluated for internal consistency using Cronbach's alpha. Cronbach's alpha verifies the consistency and reliability of analyses and ranking processes for Likert-type scales. Cronbach's alpha reliability coefficient typically ranges between 0 and 1. However, there is no lower limit to the coefficient. The closer Cronbach's alpha coefficient is to 1.0, the more significant the internal consistency of the items in the scale is [34,38], such that $\alpha > 0.9$ "Excellent"; $\alpha > 0.8$ "Good"; $\alpha > 0.7$ "Acceptable"; $\alpha > 0.6$ "Questionable"; $\alpha > 0.5$ "Poor"; and $\alpha < 0.5$ "Unacceptable" [39]. Equation (3) presents the formula for determining Cronbach's alpha.

$$\alpha = (k \div (k - 1)) \times (1 - ((\Sigma \sigma i2ki = 1) \div \sigma X2))) \quad (3)$$

where k is the number of test items, $\sigma i2$ is the variance of a single test item Xi, and $\sigma X2$ is the variance of the overall test items X.

Survey Respondents' Characteristics

A total of 18 targeted experts evaluated each sewer pipeline defect based on its severity, likelihood of occurrence, and difficulty to detect. The percentage of participants according to their professional fields is shown in Figure 3. It can be noted that 44.4% work in operation and maintenance departments, 27.8% work in project management, 22.2% work in site engineering, and the lowest percentage, 5.6%, represents individuals who work in design engineering.

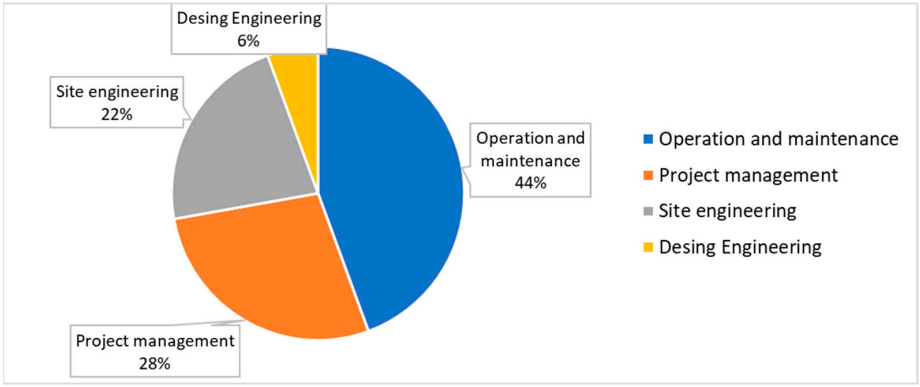


Figure 3. Participant percentages according to their professional fields.

Figure 4 illustrates the participants' past experience with working with sewer pipeline systems in Saudi Arabia. Approximately 44% of the participants possess over 11 years of experience, while nearly 33% have up to 5 years of experience, and about 22.2% have between 6 and 10 years' worth of experience.

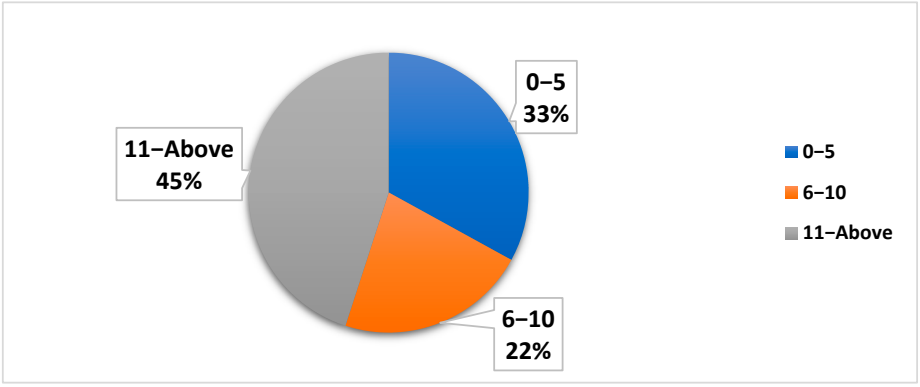


Figure 4. Participants' years of experience with sewer pipeline systems in Saudi Arabia.

4. Data Collection

After conducting face-to-face interviews, all four experts affirmed the identified defects and their contributing factors as prevalent issues within sewer pipelines. One defect was added by one of the experts (EX3) within the hydraulic category, *hydraulic overflow*, which is denoted by (D7). Ultimately, the total number of defects amounted to 15 defects. C_{27} is one of the causes related to the production and release of H_2S (D15), which was added by an expert (EX1) (refer to Table 3). Furthermore, the experts suggested possible solutions for each defect, which are reported in Table 4.

Table 4. Possible solutions for defects.

Defect	Possible Solutions	Code
D1	Making periodic visits to factories and ensuring compliance with specifications through necessary tests.	S_1
	Addressing issues underneath the pipes by placing pebbles at the bottom of the pipes in layers 20 cm thick for rocky soil and 15 cm thick for normal soil.	S_2
	Laying a gravel layer with a thickness of up to 30 cm directly above the pipe.	S_3
	Laying a subgrade layer of burial soil with a thickness of up to 30 cm to avoid the effect of tamping on the pipe.	S_4
D2	Making periodic visits to factories and ensuring compliance with specifications through necessary tests.	S_5
	Addressing issues underneath the pipes by placing pebbles at the bottom of the pipes in layers 20 cm thick for rocky soil and 15 cm thick for normal soil.	S_6
	Laying a gravel layer with a thickness of up to 30 cm directly above the pipe.	S_7
	Laying a subgrade layer of burial soil with a thickness of up to 30 cm to avoid the effect of tamping on the pipe.	S_8
D3	Protecting pipes while laying gravel and completing backfill and layering work.	S_9
D4	Protecting services during implementation.	S_{10}
	Relocating services away from the sewage line path according to technical specifications.	S_{11}
	Making the necessary reinforcements for all services intersecting with the sewage service.	S_{12}
D5	Excavating and repairing the defective parts of a pipe or a complete pipe segment as appropriate, following the standard specifications of bedding and backfilling.	S_{13}
D6	Checking joints and welds, ensuring the straightness of the pipes utilizing thread or mirrors, and checking the integrity of the head and tail.	S_{14}
D7	Constructing a new auxiliary line, taking the excess flow from a pipe's capacity.	S_{15}
D8	Considering the excessive routine flushing of parts within the preventive maintenance plan.	S_{16}
D9	Reviewing the structures and attachment points and ensuring the integrity of the welds and cables.	S_{17}
D10	Making oil traps for restaurants and factories and connecting the exits to an inspection room.	S_{18}
D11	Making traps.	S_{19}
D12	Verifying joints and reviewing the attachment and welding points.	S_{20}
	Conducting periodic testing of pipes and ensuring their safety and compliance with specifications.	S_{21}
	Regular maintenance of sewers and tree removal.	S_{22}
D13	Excavating and repairing the defective parts of a pipe or complete pipe segments as appropriate, following the standard specifications of bedding and backfilling.	S_{23}
D14	After implementation, ensuring that the lines are straight by using the mirror test.	S_{24}
	Checking pipe alignment during implementation.	S_{25}
D15	The slope of the pipe must be assessed in the design stage to ensure that the speed does not exceed 1.5 m/sec. The backdrop in the manhole should be made according to the specifications so that the height does not exceed 30 cm.	S_{26}
	Considering the excessive routine flushing of parts within a preventive maintenance plan.	S_{27}

5. Study Findings

5.1. The Probability of Occurrence of Defects and Their Impact

In this study, the participants provided evaluations of occurrence probabilities based on their experiences with sewer pipeline systems in Saudi Arabia. The relative importance index (RII) method was employed to analyze these evaluations, as discussed in the Research Methodology section. The results of this analysis are reported in Table 5. Regarding the frequency of occurrence, the defects D8 (inflow) and D10 (dumping foreign objects) were ranked at the top compared to the other defects, according to Table 5.

Table 5. The probability of occurrence of defects.

Failure	Defect Category	Defect	Probability				
		Code	$\sum W$	A	N	RII	Weighted Mean %
Pipe collapse	Structural defects	D1	54	5	18	0.6	5.96
		D2	51	5	18	0.567	5.629
		D3	60	5	18	0.667	6.623
		D4	61	5	18	0.678	6.733
		D5	54	5	18	0.6	5.96
		D6	66	5	18	0.733	7.285
Sewer system overflow (SSO)	Hydraulic defects	D7	67	5	18	0.744	7.395
		D8	68	5	18	0.756	7.506
		D9	52	5	18	0.578	5.74
		D10	68	5	18	0.756	7.506
		D11	65	5	18	0.722	7.174
		D12	64	5	18	0.711	7.064
		D13	61	5	18	0.678	6.733
		D14	56	5	18	0.622	6.181
Odor and ground water contamination	Quality defects	D15	59	5	18	0.656	6.512

After calculating the defect probability for each of the 15 defects, the second step utilized the same methodology to calculate how each parameter (i.e., economical (P1), environmental (P2), social (P3), and detection difficulty (P4)) would be impacted using the RII and weighted mean percentage, as reported in Table 6. D15 (the production and release of H_2S) was ranked the highest among other defects in terms of its impact, and it was ranked as an environmental type of defect.

5.2. Ranking Defects via the Risk Index

The risk index was used as the final step to highlight the defects' ranks based on the results obtained from the previous two steps. This step was completed to ensure the defect rankings were accurate, as shown in Table 7. Taking both probability and impact into account, the defects that ranked the highest were D10 (the dumping of fat, oil, and grease (FOG)), followed closely by D7 (hydraulic overflow) and then D8 (sediment accumulation), as reported in Table 7.

Table 6. Economical (P1), environmental (P2), social (P3), and detection difficulty (P4) parameter ranks for each defect.

Failure	Defect Category	Defect	Parameters					
				Impact			Impact	
		Code	Code	Within the Defect				
				RII	Weighted Mean %	Rank	RII	Weighted Mean %
Pipe collapse	Structural defects	D1	P1	0.7	26.033	2	0.672	6.616
			P2	0.778	28.926	1		
			P3	0.667	24.793	3		
			P4	0.544	20.248	4		
		D2	P1	0.744	30.594	1	0.608	5.987
			P2	0.6	24.658	2		
			P3	0.567	23.288	3		
			P4	0.522	21.461	4		
		D3	P1	0.8	28.916	2	0.692	6.807
			P2	0.811	29.317	1		
			P3	0.789	28.514	3		
			P4	0.367	13.253	4		
		D4	P1	0.722	26.104	3	0.692	6.807
			P2	0.789	28.514	1		
			P3	0.778	28.112	2		
			P4	0.478	17.269	4		
		D5	P1	0.733	27.615	1	0.664	6.534
			P2	0.722	27.197	2		
			P3	0.589	22.176	4		
			P4	0.611	23.013	3		
		D6	P1	0.767	27.935	2	0.686	6.752
			P2	0.778	28.34	1		
			P3	0.622	22.672	3		
			P4	0.578	21.053	4		
Sewer system overflow (SSO)	Hydraulic defects	D7	P1	0.811	28.627	2	0.708	6.971
			P2	0.856	30.196	1		
			P3	0.778	27.451	3		
			P4	0.389	13.725	4		
		D8	P1	0.778	28.807	1	0.675	6.643
			P2	0.756	27.984	2		
			P3	0.7	25.926	3		
			P4	0.67	17.284	4		
		D9	P1	0.767	28.87	1	0.664	6.534
			P2	0.733	27.615	2		
			P3	0.7	26.36	3		
			P4	0.456	17.155	4		

Table 6. *Cont.*

		D10	P1	0.789	27.843	2	0.708	6.971
			P2	0.833	29.412	1		
			P3	0.722	25.49	3		
			P4	0.489	17.255	4		
		D11	P1	0.722	28.384	2	0.636	6.26
			P2	0.756	29.694	1		
			P3	0.622	24.454	3		
			P4	0.444	17.467	4		
		D12	P1	0.7	26.695	2	0.656	6.452
			P2	0.722	27.542	1		
			P3	0.689	26.271	3		
			P4	0.511	19.492	4		
		D13	P1	0.767	28.87	1	0.664	6.534
			P2	0.689	25.941	2		
			P3	0.689	25.941	3		
			P4	0.511	19.247	4		
		D14	P1	0.711	25.6	2	0.694	6.834
			P2	0.744	26.8	1		
			P3	0.644	23.2	4		
			P4	0.678	24.4	3		
Odor and groundwater contamination	Quality defects	D15	P1	0.711	23.97	3	0.742	7.299
			P2	0.878	29.588	1		
			P3	0.8	26.966	2		
			P4	0.578	19.476	4		

Table 7. The ranking of defects based on probability and impact.

Failure	Defect Category	Defect Code	Probability		Impact		RI	Ranking
			RII	Weighted Mean %	RII	Weighted Mean %		
Pipe collapse	Structural defects	D1	0.6	5.96	0.672	6.616	0.403	12
		D2	0.567	5.629	0.608	5.987	0.345	15
		D3	0.667	6.623	0.692	6.807	0.462	8
		D4	0.678	6.733	0.692	6.807	0.469	6
		D5	0.6	5.96	0.664	6.534	0.398	13
		D6	0.733	7.285	0.686	6.752	0.503	4
Sewer system overflow (SSO)	Hydraulic defects	D7	0.744	7.395	0.708	6.971	0.527	2
		D8	0.756	7.506	0.675	6.643	0.51	3
		D9	0.578	5.74	0.664	6.534	0.384	14
		D10	0.756	7.506	0.708	6.971	0.535	1

Table 7. *Cont.*

		D11	0.722	7.174	0.636	6.26	0.459	9
		D12	0.711	7.064	0.656	6.452	0.466	7
		D13	0.678	6.733	0.664	6.534	0.45	10
		D14	0.622	6.181	0.694	6.834	0.432	11
Odor and groundwater contamination	Quality defects	D15	0.656	6.512	0.742	7.299	0.487	5

Lastly, the results of the preceding steps were combined and summarized in Table 8. Table 8 also provides a ranking of the contributing factors for each defect. For instance, considering defect D12 (root intrusion), the contributing factors are ranked as follows: first C17 (sewer maintenance practices—improper root removal), then C16 (structural defects of pipes), followed by C15 (incorrectly constructed joints), and finally C14 (inappropriate choice of joints). A summary of the complete findings can be found in Table 8. It is worth noting that the weighted mean %, along with the rank, are empty in Table 8 for defects with one contributing factor.

5.3. Reliability and Validation

The internal consistency of the utilized questions in assessing the defects was evaluated using Cronbach's alpha via SPSS. Table 9 reports the findings of Cronbach's alpha. As part of the Cronbach's alpha analysis, Table 9 includes the corrected item–total correlation, which indicates the correlation between each defect with a scaled score that excludes the defect. According to Table 9, the average Cronbach's alpha value for the assessment was $\alpha = 0.89$, suggesting that the items exhibited a high level of internal consistency among the assessed defects. The findings also suggested that dropping any question from the assessment will unlikely significantly improve Cronbach's value.

The study's findings pertaining to the defects' probabilities of occurrence and impacts offer valuable insights into the specific context of sewer pipeline systems in Saudi Arabia. To contextualize these findings in comparison to previous studies, it is important to note that few studies have explored this area with a regional focus, which makes these results particularly significant. Unlike previous research, which often used general methodologies which are applicable worldwide, this study takes a more tailored approach by integrating the experiences and evaluations of participants who have practical knowledge of Saudi Arabian sewer systems. The application of the relative importance index (RII) method to assess probability and impact is a notable methodological advancement, offering a more region-specific and contextually relevant perspective. In contrast to prior studies that might have relied on more generic fault tree analyses or cause-and-effect diagrams, this research provides a more nuanced view of sewer system defects in Saudi Arabia.

The study's findings emphasize the high probabilities of occurrence of the defects D8 (inflow) and D10 (the dumping of foreign objects) and the significant impact of D15 (the production and release of H2S) on the sewer pipeline systems. Such a focus on specific defects and their local relevance is a departure from broader studies that may not capture the unique challenges faced by Saudi Arabian sewer systems. By ranking defects and assessing their impacts across various parameters (economical, environmental, social, and detection difficulty), this study provides a comprehensive understanding of maintainability concerns. In comparison to previous research that might concentrate solely on identifying defects or examining their individual impacts, this study offers a more holistic view of the interplay between the defects' occurrence probabilities and their multifaceted impacts. This nuanced perspective serves as a robust foundation for sewer infrastructure management in Saudi Arabia and can serve as a valuable reference for future studies in similar contexts.

Table 8. Summary of the overall findings.

Failure	Defect Category	Defect	Contributing Factor(s)				Parameters				Probability		Impact		RI	Ranking
		Code	Code	Impact Within the Defect			Code	Impact Within the Defect			Mean with Associated Category %	RII	Weighted Mean %	RII	Weighted Mean %		
				RII	Weighted Mean %	Rank		RII	Weighted Mean %	Rank							
Pipe collapse	Structural defects	D1	C1	0.8	61.017	1	P1	0.7	26.033	2	15.6	0.6	5.96	0.672	6.616	0.403	12
							P2	0.778	28.926	1							
							P3	0.667	24.793	3							
							P4	0.544	20.248	4							
			C2	0.511	38.983	2											
		D2	C3	0.811	---	---	P1	0.744	30.594	1	14.7	0.567	5.629	0.608	5.987	0.345	15
							P2	0.6	24.658	2							
							P3	0.567	23.288	3							
							P4	0.522	21.461	4							
		D3	C4	0.722	---	---	P1	0.8	28.916	2	17.3	0.667	6.623	0.692	6.807	0.462	8
							P2	0.811	29.317	1							
							P3	0.789	28.514	3							
							P4	0.367	13.253	4							
		D4	C5	0.756	---	---	P1	0.722	26.104	3	17.6	0.678	6.733	0.692	6.807	0.469	6
							P2	0.789	28.514	1							
							P3	0.778	28.112	2							
							P4	0.478	17.269	4							
		D5	C6	0.744	---	---	P1	0.733	27.615	1	15.6	0.6	5.96	0.664	6.534	0.398	13
							P2	0.722	27.197	2							
							P3	0.589	22.176	4							
							P4	0.611	23.013	3							
		D6	C7	0.8	---	---	P1	0.767	27.935	2	19.1	0.733	7.285	0.686	6.752	0.503	4
							P2	0.778	28.34	1							
							P3	0.622	22.672	3							
							P4	0.578	21.053	4							

Table 8. *Cont.*

Sewer system overflow (SSO)	Hydraulic defects	D7	C8	0.8	---	---	P1	0.811	28.627	2	13.4	0.744	7.395	0.708	6.971	0.527	2
							P2	0.856	30.196	1							
							P3	0.778	27.451	3							
							P4	0.389	13.725	4							
		D8	C9	0.811	54.478	1	P1	0.778	28.807	1	13.6	0.756	7.506	0.675	6.643	0.51	3
							P2	0.756	27.984	2							
							P3	0.7	25.926	3							
			C10	0.678	45.522	2	P4	0.67	17.284	4							
		D9	C11	0.744	---	---	P1	0.767	28.87	1	10.4	0.578	5.74	0.664	6.534	0.384	14
							P2	0.733	27.615	2							
							P3	0.7	26.36	3							
							P4	0.456	17.155	4							
		D10	C12	0.767	---	---	P1	0.789	27.843	2	13.6	0.756	7.506	0.708	6.971	0.535	1
							P2	0.833	29.412	1							
							P3	0.722	25.49	3							
							P4	0.489	17.255	4							
		D11	C13	0.811	---	---	P1	0.722	28.384	2	13	0.722	7.174	0.636	6.26	0.459	9
							P2	0.756	29.694	1							
							P3	0.622	24.454	3							
							P4	0.444	17.467	4							
		D12	C14	0.678	23.643	4	P1	0.7	26.695	2	12.8	0.711	7.064	0.656	6.452	0.466	7
			C15	0.7	24.419	3	P2	0.722	27.542	1							
			C16	0.722	25.194	2	P3	0.689	26.271	3							
			C17	0.767	26.744	1	P4	0.511	19.492	4							
		D13	C18	0.711	20.382	3	P1	0.767	28.87	1	12.2	0.678	6.733	0.664	6.534	0.45	10
			C19	0.6	17.197	5	P2	0.689	25.941	2							
			C20	0.778	22.293	1	P3	0.689	25.941	3							
			C21	0.644	18.471	4	P4	0.511	19.247	4							
			C22	0.756	21.656	2											
		D14	C23	0.733	---	---	P1	0.711	25.6	2	11.2	0.622	6.181	0.694	6.834	0.432	11
							P2	0.744	26.8	1							
							P3	0.644	23.2	4							
							P4	0.678	24.4	3							

Table 8. *Cont.*

Odor and groundwater contamination	Quality defects	D15	C24	0.789	26.792	1	P1	0.711	23.97	3	---	0.656	6.512	0.742	7.299	0.487	5
			C25	0.744	25.283	2	P2	0.878	29.588	1							
			C26	0.667	22.642	4	P3	0.8	26.966	2							
			C27	0.744	25.283	3	P4	0.578	19.476	4							

Table 9. Summary of the results from the Cronbach's alpha reliability test.

Defect Code	Corrected Item–Total Correlation	Cronbach's Alpha If the Defect Was Excluded from the Survey
D1	0.66	0.88
D2	0.32	0.89
D3	0.75	0.88
D4	0.66	0.88
D5	0.41	0.89
D6	0.5	0.89
D7	0.74	0.88
D8	0.42	0.89
D9	0.69	0.88
D10	0.27	0.9
D11	0.38	0.89
D12	0.74	0.88
D13	0.7	0.88
D14	0.44	0.89
D15	0.75	0.88
Average Cronbach's alpha α		0.89

Tables 5–9 in this study provides a comprehensive framework for assessing the critical aspects of sewer pipeline systems in Saudi Arabia. These tables collectively illuminate the complexities of defect occurrence, the defects' multi-dimensional impacts, their rankings based on probability and impact, contributing factors, and the reliability of the assessment. In Table 5, the study presents an in-depth evaluation of the probability of defects occurring in the context of Saudi Arabian sewer systems. This examination is essential for understanding the specific vulnerabilities within the infrastructure. Table 6 delves into the impact of these defects across various parameters, highlighting the economic, environmental, social, and detection difficulty dimensions. It provides a nuanced view of the consequences that these defects may have, offering valuable insights into the overall significance of each defect category. Table 7 builds upon the probability and impact assessment, ranking the defects based on their risk index values. This ranking offers a clear indication of the most critical issues that require immediate attention in terms of management and maintenance. Moving on to Table 8, it provides a succinct summary of the findings, offering an overview of the contributing factors to these defects. This summary aids in understanding the root causes of these issues, ultimately guiding decision-makers towards more targeted intervention strategies. Finally, Table 9 validates the assessment's reliability, underlining the consistency and robustness of the study's methodology and findings.

Together, these tables form a cohesive narrative. They first identify the most probable and impactful defects, then rank them, explore their contributing factors, and lastly confirm the reliability of the assessment. This multi-faceted approach to analyzing sewer system defects in Saudi Arabia equips stakeholders with a comprehensive understanding of the challenges and the tools required for effective management and decision-making in maintaining the country's sewer infrastructure. The synthesis of these tables serves as a valuable reference not only for addressing existing issues but also for setting the course for future research and infrastructure management strategies in Saudi Arabia and potentially in other regions facing similar challenges.

6. Discussion

Concerning the results obtained and when discussing each category separately to clarify the probability of the occurrence of each defect and its rank, the defects belonging to the structural category are examined first. It can be seen that defect D6 (joint defect), caused by welded joint weakness due to the misalignment of plastic pipes or joints, especially spigot and socket joints for rigid pipes, has the highest probability, with an RII value of 0.733, as reported in Table 5. This is followed by D4, with an RII value of 0.678, which is caused by failed utilities located in the vicinity of a wastewater pipeline. This defect can result in soil disturbances and possible changes in bedding configuration, ultimately leading to wastewater pipe failure. Then there is D3, which occurs due to tampering and damage to sewage works by private and/or unknown persons, with an RII value of 0.677. At the same time, D1, with a primary cause due to excessive loading and poor pipe bedding, which can cause pipe cracks and fractures, and D5, which is caused by improper installation and material, have equal RII values of 0.66. The lowest RII defect was found for D2, which results from excessive external loadings, thermal soil loads, or other mechanical causes, with a result of 0.567.

Transitioning to the second category, which includes defects in the operational (hydraulic) category, it is evident that D8 (sediment accumulation) and D10 (the dumping of FOG) carry the highest probability, sharing an RII value of 0.756. D7 and D11 follow them, with RII values of 0.744 and 0.722, respectively. Then, there are D12 and D13, with RII values of 0.711 and 0.678, respectively. The lowest defects were D14 and D9, with RII values of 0.622 and 0.578, respectively. In contrast, the third category (quality defects) has only one defect (D15); see Table 3 for the causes of these defects.

In relation to the assessed impacts, it is observed that the influence of defects varies across each parameter. In addition to the difference in rank, the parameters' roles in changing the defects' rankings can also be seen in Table 6. For example, D3 and D4 have the most impact in the structural category, each with a relative importance index (RII) value of 0.692. When moving to the hydraulic category, D7 and D10 have the most impact, with the same RII value of 0.708, while in the quality category, D15 has an impact with an RII value of 0.742; when compared as an overall impact between categories, this category has the highest impact, as reported in Table 6.

The overall ranking of all defects was calculated by combining the probabilities and impacts using the risk index (RI) values. The three highest defects, D10, D7, and D8, have RI values of 0.535, 0.572, and 0.510, respectively, for the hydraulic category. This is logical since they happen often and, in the case of sewage overflows, will cause traffic jams and the constant involvement of maintenance teams, driving up costs and making the environment more vulnerable to several diseases. The fourth and fifth highest defects were D6 (RI = 0.503) and D15 (RI = 0.487), respectively. However, it is worth noting that there is little variation in the reported RII and RI values in this study, which suggests that the defects assessed are nearly equally important. The overall findings are reported in Table 8.

It is important to note that most of the causes of these defects, as reported in Table 8, and system failures, which increase the burdens of operation and maintenance, are either design- or construction-related. Therefore, in order to avoid these issues, maintenance teams should be involved in the design phase because their requirements are crucial for minimizing the likelihood of these defects occurring. Employing effective and qualified technical staff at the stage of implementing sewer pipelines and carrying out necessary tests in the presence of a maintenance team will guarantee the system's best performance during its lifecycle and prevent the need for extensive rehabilitation and costly repairs.

Possible solutions for reducing sewer pipeline defects were proposed by experts and are shown in Table 4. Various defects have one solution, and others have more, so those with more than one solution were analyzed to discover the most appropriate solution among them. It is possible to conclude that most solutions that follow the technical specifications of sewer lines in Saudi Arabia. With this in mind, it is vital to ensure that sewer pipelines in Saudi Arabia are appropriately designed and built according to technical specifications

to ensure that they are adequately maintained and to reduce the number of defects caused by inadequate design or construction. The Cronbach's alpha result, shown in Table 9, was 0.89, indicating the consistent reliability of the survey questions and collected data.

7. Conclusions

This study assessed 15 sewer pipeline defects and the maintainability of the system in Saudi Arabia. These defects were identified based on the literature and refined by experts through interviews. The experts selected for this study maintain qualification criteria that enabled them to critique and evaluate each defect's probability and impact.

The impact involves four parameters: maintenance costs, social inconvenience, environmental risks, and the difficulty of detection, as reported in Table 6. A total of 15 defects were identified, in addition to their possible causes and recommended solutions. Experts then evaluated them to arrive at their RI values, signaling the criticality of each. At the design stage, the designers can use the output of this research to optimize their selections. The sewer system is a vital system in infrastructure facilities. Eliminating unfavorable design decisions and increasing awareness of recurring issues triggered by design or implementation errors can help achieve greater maintainability. This study focused on sewer pipelines and their outputs. It is important to highlight that this study reported minimal variations in RII and RI values, indicating that the identified defects are of almost equivalent importance. As for the study's findings, they can be applied in Saudi Arabia and other countries with similar infrastructure characteristics since sewage line systems, specifications, and standards differ from one country to another. Specifically, the findings of this study have implications for design teams and planners in Saudi Arabia because they provide valuable insights into sewer system design, especially in the form of improved maintainability, which leads to reduced maintenance costs, better system performance, and improved service quality. Thus, making the right decisions in the early stages of design and implementation can mitigate the negative effects of customer complaints and obstructed traffic, reducing environmental pollution and associated costs. However, some limitations exist. Firstly, sewer pipeline maintainability studies are scarce, providing little comparable benchmarking data. The authors collected data from various research articles, case studies, and reports; nevertheless, the experts' interviews helped shape a considerable part of the understanding of sewer pipeline defects and maintenance. On the other hand, the authors endeavored to maintain an analysis of the input and the evaluations provided by the experts that was as balanced as possible. Secondly, the study took place in specific locations since the participating experts were distributed just in two cities, Riyadh and Jizan, which do not necessarily coincide with other geographical locations. Engineering, construction, and maintenance practices may vary geographically, so it is logical to assume a variability factor when applying the results of this study to multiple separate locations.

In summary, this study rigorously examined the maintainability of sewer pipeline systems in Saudi Arabia, assessing 15 defects identified via expert evaluations. The impact parameters, encompassing maintenance costs, social inconvenience, environmental risks, and the difficulty of detection, were analyzed (as depicted in Table 6). The findings reveal a critical insight into the significance of these defects, with minimal variations in risk index (RI) values, underscoring their equivalent importance. This insight can serve as a valuable tool for designers and planners not only in Saudi Arabia but also in countries sharing similar infrastructure characteristics. By incorporating these findings into the early stages of sewer system design, decision makers can significantly enhance maintainability, leading to reduced maintenance costs, better system performance, and improved service quality. These benefits translate into mitigating negative customer complaints, alleviating traffic disruptions, and reducing environmental pollution, thus minimizing associated costs.

To apply the positive outcomes observed in certain countries to other Arabian nations, policymakers and investors should prioritize infrastructure development strategies that emphasize maintainability and defect prevention. International collaboration and knowledge-sharing platforms can facilitate the transfer of best practices and expertise

between nations. Additionally, establishing standardized guidelines and specifications for sewer system design and maintenance across Arabian countries can ensure a consistent and effective approach to addressing common infrastructure challenges.

Considering the study's limitations, future research directions should focus on enhancing sewer pipeline maintainability studies by expanding the sample size and geographical coverage to account for regional variations in engineering and maintenance practices. Incorporating data-driven approaches, such as natural language processing and CCTV inspection, will provide a more comprehensive understanding of defect occurrences and their impact. Furthermore, exploring the interactions between multiple defects and simulating their combined effects can offer a more holistic perspective on sewer system maintainability. Finally, researchers should delve into the repairability criteria of pipelines and their long-term impacts to develop strategies for sustainable and resilient infrastructure systems.

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