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Urban water supply risks assessment under tropical climate

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The urban water supply system in tropical countries faces various physical risks, including pipe failures due to aging, material type, soil conditions, flooding, extreme weather events, and traffic loads. This study focuses on urban water supply risks for eight zones of Brunei-Muara district. A risk assessment using a data-driven matrix reveals Zones D2 and D6 as very high-risk areas, experiencing monthly average leaks of 880 and 471, respectively. These zones, characterized by low elevation and susceptibility to flooding during heavy rainfall, pose significant threats to water quality and public health due to the potential contamination of drinking water. Analysis of pipe data highlights that pipes with a diameter of 100 mm are more prone to leaks, with ductile iron pipes being particularly susceptible to failures. Brunei is actively exploring the implementation of digitalization and advanced technologies such as the application of GIS, deploying real-time water quality sensors, and real-time pressure monitoring integrated with SCADA systems to mitigate these risks.

All life forms depend on water, but anthropogenic activities endangering it increasingly, making it harder for people to access clean water sources worldwide[1]. The escalating global population exacerbates the strain on freshwater retrieval, posing challenges to economic development through water shortages and scarcity. Concurrently, the specter of climate change looms large with extreme weather events (intensive precipitation and high temperatures), further compromising water availability and quality in tropical countries. Despite efforts, the United Nations reports that 2.2 billion people still lack access to safe drinking water[2], perpetuating cycles of poverty[3–6] and contributing to a staggering 1.4 million deaths from diarrhoea in 2019[7]. The sustainable development of urban areas relies on dependable water delivery systems that can adequately fulfil water requirements and have the resilience to withstand drought periods[8].

Historical data highlights the crucial importance of urban water supply infrastructure in reducing the spread of infectious illnesses[9–10]. A tropical country like Brunei Darussalam Key Indicator reported reaching an estimated population of 459,500 in 2019. Brunei has reduced water consumption from 460 L per capita per day (lpcd) to 380 lpcd in 2018 and dropped by another 10 lpcd, 370 lpcd in 2020. Even though there is a drop in water consumption, Brunei Darussalam is still considered to be using water at a higher rate than neighbouring countries, where most only consume around 200 to 250 lpcd. The government targets reducing water consumption to 290 lpcd to reach the 2035 vision, where reducing water usage may result in sustainable life for Brunei Darussalam. The Ministry of Development (MOD) has been working on implementing a strategic development plan to preserve water resources and manage water supply efficiently. This includes raising public awareness of water conservation and setting priorities in the Strategic Plan to tackle non-revenue water (NRW), which affects the economy and causes water system loss. Despite the slight improvement in the recent SDG 2021 report, there is an ongoing concern about Brunei's water quality due to heavy rainfall, as stated by the Public Works Department. Heavy rainfall and floods may increase organic material content in the catchment areas, giving off murky water. This is proven by several residents' complaints of "yellowish water" in some areas[11]. Aside

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from the water quality issue, it is believed that the water system in Brunei experiences about 40% water system loss, which affects the economy utilizing NRW[12]. NRW water includes unaccounted-for consumption due to physical (real) and commercial (apparent) losses. Physical losses are pipe-related, where water supplied does not reach the consumer due to leakages in the pipeline and overflow storage tanks.

Meanwhile, commercial losses are due to unauthorised consumption, such as illegal water tapping and inaccuracy in water metering. Due to the high percentage of non-revenue water, one of Brunei's current strategic plans is to reduce non-revenue water. This study assesses the physical risks of pipe leaks in the network system. The objectives of this study are (i) understanding the existing water supply system in the Brunei-Muara district, (ii) identification of potential areas susceptible to water leaks, and (iii) preparing a risk assessment map based on vulnerability to leaks.

Examining the water risks is crucial as they may leave serious impacts due to poor water management. There are several repercussions of water pipe collapse. The consequences include property loss, expenses for repair and remediation, negative impact on human health, environmental harm, and consumer discontent[13–14]. Water-borne diseases may spread, and water shortages will occur more often if not handled well. Not only that, disregarding water risks will cause a drop in the economy, and the world will not be able to achieve sustainability. There are several categories of water risks, but the most common are physical, regulatory, and reputational risks. The main focus of the study is the physical risk, which is related to the quality of water and the quantity, whether it may be too much or too little, i.e., flooding and scarcity[15]. One of the concerns stems from the piping systems, such as how old the pipe is, its material, where the pipe is laid, and what kind of soil surrounds it. The study was conducted by analysis of leaks in Brunei-Muara district over the past five years. The study collects secondary data from the Department of Water Service (DWS). The study is essential for Brunei to improve the water supply management. Performing risk assessments on the existing water supply may help determine the potential hazards and the severity of the threats to the water supply. This gives an idea of which area the authority should give high priority and more effort to improving the water efficiency and quality. Also, by doing so, strategies can be worked out to mitigate or reduce the risks.

Urban water supply systems in tropical climates face unique challenges due to natural and anthropogenic factors, including extreme weather events, flooding, and aging infrastructure. These issues are not confined to Brunei but are observed globally in cities with similar climatic and urbanization patterns. For instance, cities like Jakarta, Manila, and Bangkok also grapple with high non-revenue water (NRW) percentages due to pipe leaks, illegal connections, and insufficient maintenance of aging infrastructure[16]. Similarly, in Lagos, frequent flooding and poor drainage exacerbate the risks to water supply networks[17]. Comparative studies reveal striking similarities in risk factors. For example, Dhaka, Bangladesh, has reported frequent pipe failures linked to low-quality materials, improper soil compaction, and high groundwater fluctuations[18]. In Jakarta, the integration of Geographic Information Systems (GIS) and Supervisory Control and Data Acquisition (SCADA) systems has improved leak detection but requires significant investment to sustain long-term operations[19]. Bangkok's experience demonstrates how urban density and high consumption rates intensify NRW issues, emphasizing the need for policy intervention and public awareness campaigns[20]. These parallels underscore the importance of adopting innovative technologies across tropical urban centres, such as real-time monitoring systems and predictive maintenance. The present study focuses on the Brunei-Muara district, addressing gaps in localized risk assessments by drawing insights from these global experiences. This research aims to provide transferable solutions for tropical cities facing similar risks by contextualising Brunei's challenges within a broader framework.

Methodology
The study's design was done qualitatively by collecting data from DWS and the Government's Open Data, accessible at any time, to assess the risk and vulnerability of the Brunei population to waterborne disease due to water leaks.

There are three steps involved in risk assessment: risk identification, risk analysis, and risk evaluation[21]. Risk identification includes identifying threats to the system. List the hazards in the water system, from the water source to the treatment and storage and, lastly, distribution to the consumers. Risk Analysis is where the likelihood and consequences of the risks are calculated. There are three types of measuring tools for risk analysis: matrix model, probabilistic model, and indexing model. The matrix model is the most straightforward decision support tool among the other two; therefore, this study uses a matrix model. The probabilistic model focuses on specific events, compares risk failures, and calculates event probabilities; the technique is data-intensive and costly. Risk evaluation is done at the last step to determine whether the risks should be considered or can be neglected if they do not majorly impact the system.

Data collection
Data was collected from the Department of Water Services under the Public Works Department at Tasek Lama. The Operation and Maintenance Unit of DWS granted monthly reports of the Operation Control Centre (OCC) from 2015 to 2020, during which leak records were obtained. In pipe network design or analysis, it is crucial to incorporate data validation and quality control techniques to guarantee the correctness and dependability of the results. Verifying input values (e.g., pipe sizes and flow rates) conform to realistic or acceptable parameters. Additionally, focus was placed on validating that the geographical coordinates of the network are accurate and aligned with the appropriate spatial reference system.

The data includes zones and a list of villages in each zone, monthly leaks according to zones in the Brunei-Muara district, statistics of pipe failure zone-wise, and pipe materials and diameter. The data related to population was obtained from the 2016 Population and Housing Census Final Report. Furthermore, recorded cases of infectious diseases in Brunei were obtained from the country's online data platform. The platform is open to the public and contains 600 datasets from different government authorities. The infectious diseases document

			Severity				
			Insignificant 0.2	Minor 0.4	Moderate 0.6	Major 0.8	Catastrophic 1
Likelihood	Once per day	1	Moderate 0.2	High 0.4	High 0.6	Very High 0.8	Very High 1
	Once per week	0.8	Low 0.16	Moderate 0.32	High 0.48	High 0.64	Very High 0.8
	Once per month	0.6	Low 0.12	Moderate 0.24	Moderate 0.36	High 0.48	High 0.6
	Once per year	0.4	Very Low 0.08	Low 0.16	Moderate 0.24	Moderate 0.32	High 0.4
	Once every 10 years	0.2	Very Low 0.04	Very Low 0.08	Low 0.12	Low 0.16	Moderate 0.2

Table 1. Risk Matrix with weightage score[22].

Severity	0.2	0.4	0.6	0.8	1
Likelihood	No waterborne diseases requiring hospital treatment	No waterborne diseases but requiring hospital treatment	Waterborne diseases requiring hospital treatment	Severe waterborne diseases requiring urgent hospital treatment	Very severe life-threatening event due to waterborne diseases

Table 2. Severity of impact and the likelihood.

Risk score	Risk Indicator	Description
0.00–0.08	Very Low	Less than 1% of the exposed population; frequency of at least once per year to per 10 years
0.081–0.16	Low	Less than 1% of the exposed population; frequency of at least once per month to per year
0.17–0.36	Moderate	1–5% of the exposed population; frequency of at least once per week to per month
0.37–0.64	High	5–30% of exposed population; frequency of at least once per week to per month
> 0.64	Very High	More than 30% of the exposed population; frequency of at least once per day to per week

Table 3. The risk score.

provides cases that were encountered from 2012 to 2018. This includes food and waterborne diseases listed as Cholera, Dysentery Shigella, Food Poisoning, Gastroenteritis, Hepatitis A, Salmonella, and Campylobacter Upsaliensis. After data collection, the data is organized and then analysed using Microsoft Excel. The cases provided were district-wise; hence, to find out the vulnerability, it was assumed that the incidence rate of the diseases in the Brunei-Muara district was equal throughout the zones.

Data analysis
The data obtained from the authorities were evaluated using Microsoft Excel to determine the zonal population and area, the average leaks per month, the incidence rate of waterborne diseases, and pipe failures. The zones were mapped using ArcGIS 10.2. The data related to each zone and population were obtained and linked as an attribute table concerning the map produced by ArcGIS 10.2. The monthly leaks throughout the eight zones from 2015 to 2020 were to determine the average monthly leaks for each zone. Pipe materials and pipe sizes were obtained to determine which pipe diameter and which material caused the most leaks.

Risk matrix
The risk assessment was done using the matrix shown in Table 1. To determine the exposed population, the incidence rate of waterborne diseases was used in this study whereby;

$$\text{Exposed population} = \text{Incidence rate} \times \text{Population of the zone.}$$

The risk is determined by multiplying the likelihood of an impact with the severity.

$$\text{Risk} = \text{Likelihood} \times \text{Severity.}$$

Assessing the likely impact of the severity of distributed water supply through the pipeline is based on the following severity scale resulting from waterborne diseases, as shown in Table 2.

The risk score is based on the weightings of the severity and likelihood, as shown in Table 3.

Study area

Brunei Darussalam, one of Southeast Asian countries, is located on the northern coast of Borneo Island, with an area of 5,675 km^2 and a population of about 4,50,000. The Limbang River divides the nation into two enclaves because Sarawak, a Malaysian state, is its border. There are four districts: Brunei-Muara, Tutong, Kuala Belait, and Temburong. Brunei-Muara district is the smallest, having an area of 571 km^2. The region was estimated to have a population of 319,500 with a population density of 560/km^2. It is known to be the most populous district compared to other districts, as it has a large urban area. This district is also where the capital city, Bandar Seri Begawan, is situated.

Brunei Darussalam is an equatorial country with a tropical climate that experiences high rainfall and temperatures year-round. Climate variability usually ensues from the monsoon winds. Brunei undergoes monsoon periods, during which the northern monsoon occurs from December to March and the southeast monsoon from June to October. The total average annual precipitation is an estimated 2,722 mm. The country encounters two rainy seasons: the first from September to January and the second from May to July. The temperature is relatively uniform throughout the year, with an annual average of 27.9 °C, ranging from 23.8 to 32.1 °C, though there may be an increase in temperature due to global warming. The drought months of March and April are the warmest. The humidity of the country is about 82% all year round. It was found that areas around Berakas, Sengkurong, Mulaut, and Kilanas are susceptible to flooding during heavy rainfall.

The water network in the Brunei-Muara district is being monitored by separating the area into eight zones. Zone D1 in the northeastern Brunei-Muara district includes Mukim Serasa and Mukim Mentiri villages. However, some parts of STKRJ Tanah Jambu, Kampung Pengkalan Sibabau, Kampung Mentiri, and Kampung Perpindahan Mentiri are not within the zone. Zone D_1 covers an estimated area of 66.35 km^2 with a population density of 682.69/km^2, including 60% of Kampung Mentiri and 70% of Kampung Perpindahan Mentiri. Zone D_2 has an area of 73 km^2, and the population density is 970.27/km^2. Comprises Mukim Berakas A (excluding Kampung Terunjing), Mukim Berakas B, Diplomatic Area, Kampung Belimbing, and STKRJ Tanah Jambu. Zone D3 monitors the area around most of Mukim Kota Batu, starting from Kampung Sungai Besar towards the capital area, Mukim Kianggeh, which includes Bandar Seri Begawan, 40% of Kampung Mentiri, 30% of Kampung Perpindahan Mentiri, and Kampung Pengkalan Sibabau. Zone D3's area is estimated to be 29.63 km^2, with a population density of 601.45/km^2. Zone D4 encloses part of Mukim Gadong B, specifically Kampung Beribi, Kampung Kiarong, Kampung Kiulap, Kampung Menglait, and Kampung Jangsak. The area is about 17.74 km^2, with the highest population density of 1061.87/km^2. The high density is due to the high land use in commercial areas, which are the most concentrated zones. Zone D5 includes villages from Mukim Gadong A; the rest of Mukim Gadong B is not included in Zone D4 and Kampung Terunjing. The area is approximately 62.43 km^2, with a population density of 842.69/km^2. Zone D6 includes mainly villages from Mukim Pengkalan Batu, partial villages of Mukim Kilanas, and the whole of Mukim Sengkurong. The area is 175.42 km^2, with a population density of 326.90/km^2. Zone D7 includes the remaining villages of Mukim Kilanas, Kampung Parit, and Kampung Tumasek from Mukim Kianggeh. The area is 18.23 km^2, with a population density of 435.76/km^2. Lastly, zone D8 encompasses the southern part of Brunei-Muara district, approaching the border of Sarawak, and this includes Mukim Burong Pingai Ayer, Mukim Tamoi, Mukim Permau, Mukim Sungai Kebun, Mukim Saba, Mukim Lumapas, a few villages under Mukim Kota Batu, and Kampung Junjungan under Mukim Pengkalan Batu. The area is 98.12 km^2 with a population density of 217.2/km^2. Despite having a larger area, this zone has the lowest population density due to its abundant forest area and low housing area. The pipe network zones in the Brunei-Muara district retrieved from ArcGIS 10.2 are shown in Fig. 1a and b.
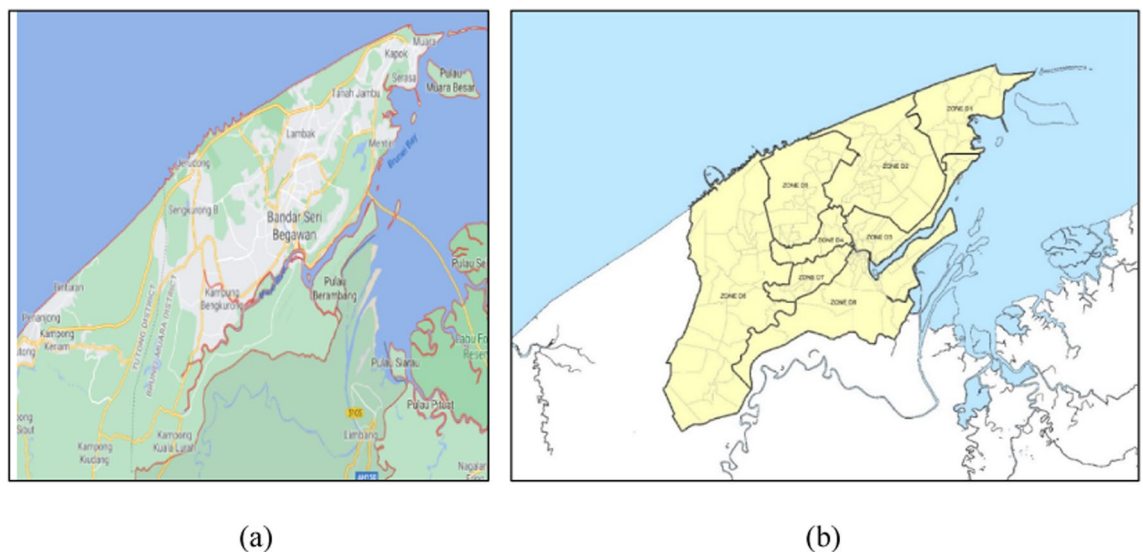

(a)   (b)

Fig. 1. (**a**) Map of Brunei-Muara (Source: Google Maps) (**b**) Pipe network zones mapped using ArcGIS 2.0.

River basins	Location	Catchment area (km²)
Brunei river	Brunei-Muara district	360
Tutong basin	Tutong district	1,300
Belait basin	Belait district,	2,700 (Largest river basin)
Temburong basin	Temburong district	430 (Smallest river basin)

Table 4. Brunei river basins[23].(source: Department of Water Service, 2023).

Year	2015	2016	2017	2018	2019
Water Production (1000 m³)	152,471	156,225	160,181	162,397	165,209
Water Consumption (1000 m³)					
Domestic	78,863	76,896	72,442	72,371	79,154
Commercial	8855	8163	7700	7528	8368

Table 5. Water Production and Consumption from 2015 to 2019[24].

Brunei Darussalam entirely relies on surface water to provide potable water to the population. However, it is said that a small quantity of groundwater has been discovered, but no further work has yet been done on the matter. The water resources come from four main river basins, as shown in Table 4.

Brunei Darussalam has four operational dams in Mengkubau and Tasek Lama in the Brunei-Muara district, as well as Benutan and Ulu Tutong, Tutong. The Ulu Tutong Dam has a storage capacity of up to 76 million cubic metres. The Tasek reservoir is used for water supply and has a total capacity of 13,000 m³; its catchment area is 2.8 km². The Benutan Dam, an impounded reservoir, regulates the National Forest Reserve of Temburong. The water pipe network in Brunei spans 2,920 km, five times the length of Brunei's coastline. The Tutong River has a total storage capacity of 45 million m³ and a catchment area of 28.6 km². The water production is estimated to be 167.9 million litres per day (MLD), or about 460 Mm³/yr. In Brunei, 77% of water resources are for domestic and commercial use, 18% are for the oil and gas industry, and 5% are for irrigation[22]. The water consumption and production from 2015 to 2019 is shown in Table 5, which indicates that water demand is well met through water production.

The country's water tariff has been the same throughout the years, where domestic water supply is charged at B\$0.11/m³ for the first 54.54 m³ and B\$0.44/m³ when it exceeds 54.54 m³. The drinking water in Brunei Darussalam is entirely governed by the Department of Water Services/Public Works Department (DWS/PWS) under the Ministry of Development. DWS has to manage and preserve water resources to achieve efficient sustainability. The water quality standards comply with the World Health Organisation's guidelines for drinking water quality. An updated water tariff system and a Unified Smart Metering System with tiered prices for residential, commercial, and raw water are featured in the authority's strategic goals to achieve sustainability in the water supply network. This progressive pricing structure better represents water production costs and promotes water efficiency, ensuring water supply sustainability[24].

Results and discussion

The study finds that the major factor contributing to leaks is aged pipes affected by flooding. The total annual leaks in Brunei-Muara district increased from 2015 to 2019 (Fig. 2).

Variations in pressure can lead to pipe damage inside the distribution network. Particularly in places with aging infrastructure, high pressure can result in leaks, cracks, and breaks in the water main[25]. The climate is recognized as a prominent element that influences the occurrence of pipe collapse[26], and Brunei, a tropical country, is already witnessing an extreme climate with high temperatures and intensive precipitation. Standard pipe failure modes include longitudinal split, pipe wall rupture or tear, and leaking joint. The leak increase (143/year) indicates that the pipes are getting worn out and must be replaced soon. The average leaks per month were also calculated to determine which zone has a high number of leaks likely to occur. Based on Fig. 3, it is observed that zone D2 has the highest average leaks, followed by zone D6, and the lowest is zone D7. Aside from aging pipes, both zones are known to have high potential flood-prone areas with low elevation. In addition, Lambak Kanan has long been experiencing low pressure, which indicates there are probably many leak points around the area.

A study has been done by the Leak Management Unit of DWS, PWD, and the engineer performed leak detection using the District Metered Area. The annual zone-wise leaks from 2015 to 2020 are shown in Fig. 4. The graph shows a consistent trend with an increasing number of leaks year by year.
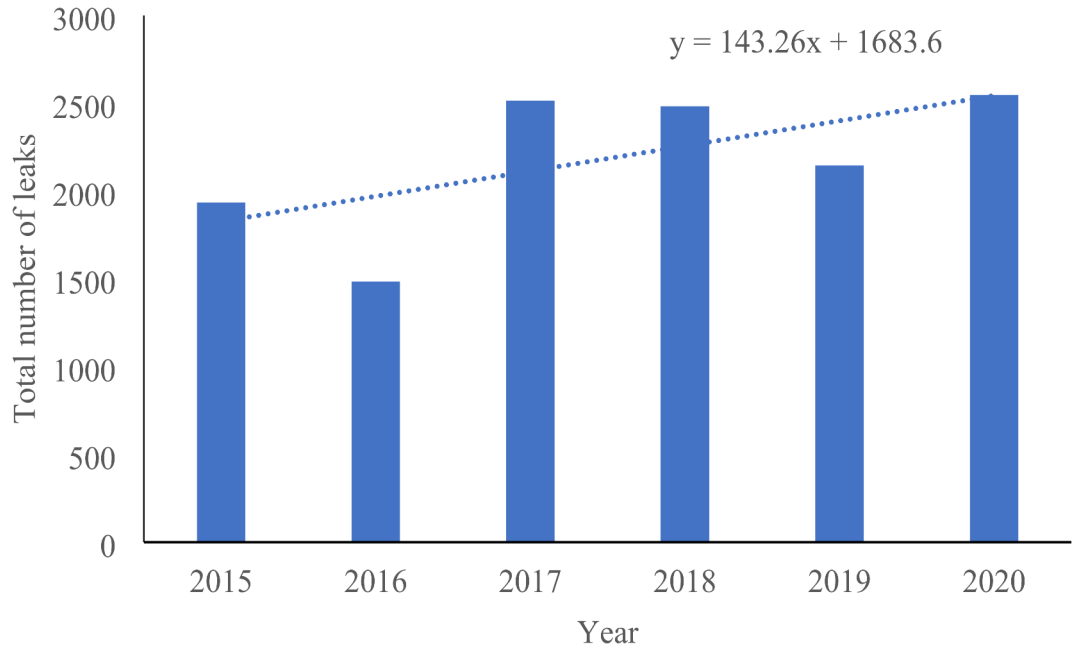
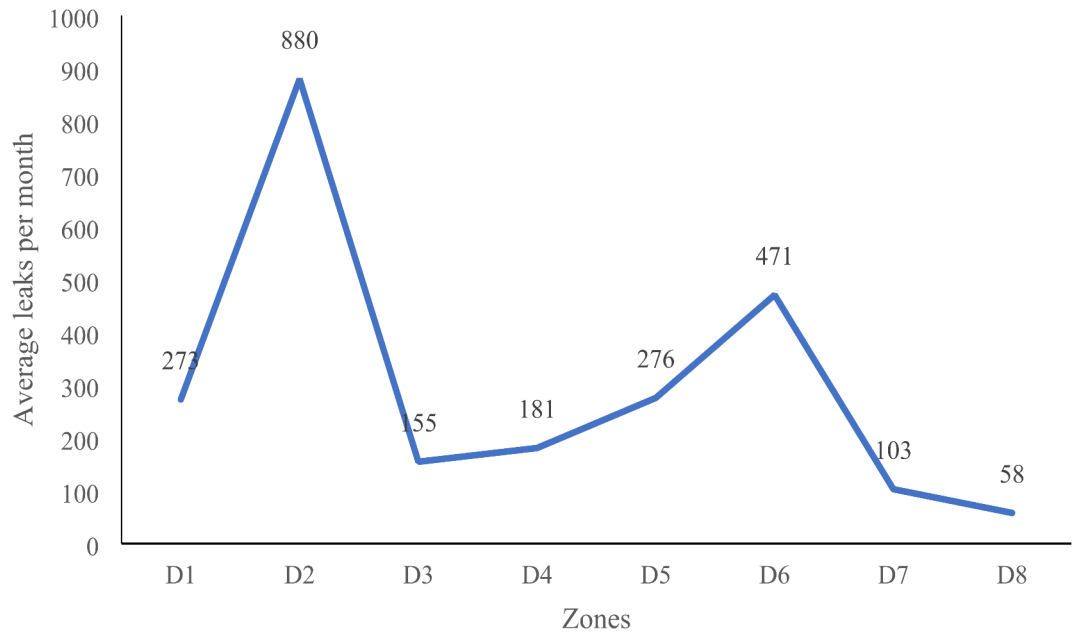**Fig. 2**. Total annual leaks in Brunei-Muara district.

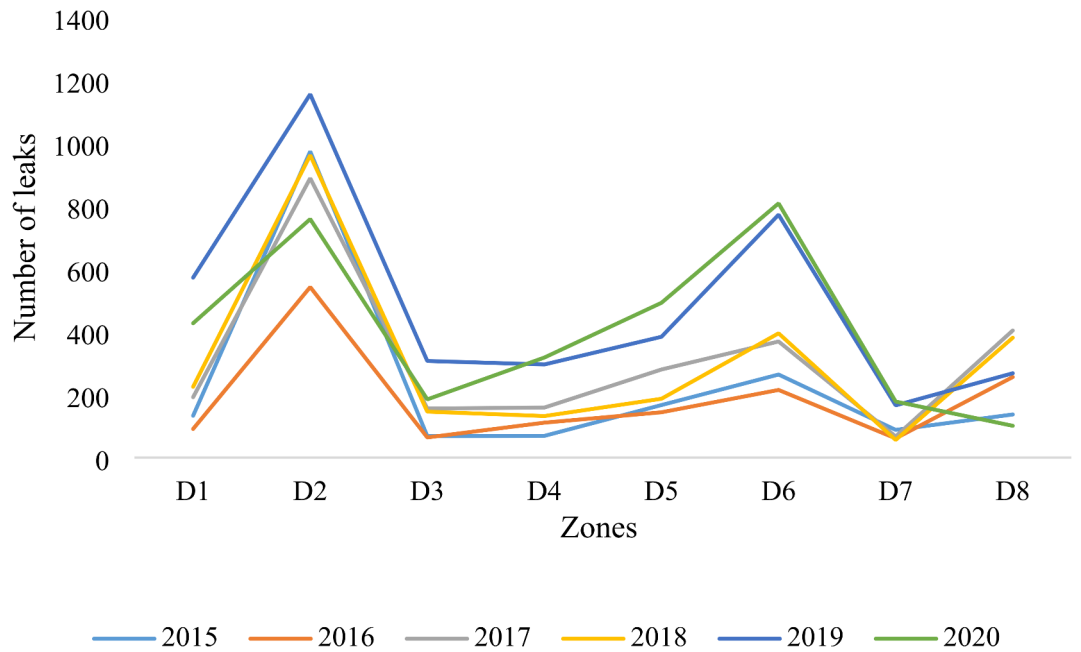**Fig. 3**. Average leaks per month in Brunei-Muara district.

Fig. 4. Annual zone-wise leaks in Brunei-Muara district.

The total number of pipe leaks with respect to total rainfall from 2015 to 2020 were plotted in Fig. 5 and found a strong correlation with total rainfall having a correlation coefficient of 0.88.

The impacts of water leaks on water quality were analysed based on data related to water-borne diseases. Data on infectious diseases was obtained online through the data.gov.bn website. A list of cases in Brunei from 2012 to 2018 is given in datasheet form. Several types of diseases are listed, including food and water-borne diseases. Brunei's most common food and waterborne diseases are Gastroenteritis, Food Poisoning, and Salmonella. Other diseases which rarely occur include Dysentery Shigella, Hepatitis A, Para/Typhoid Fever, and Campylobacter Upsaliensis. There are no recorded cholera cases, which indicates that Brunei is safe from cholera. Table 6 shows the overall instances of waterborne diseases the country has encountered from 2012 to 2018.

A graphical representation of the cases of gastroenteritis is shown in Fig. 6. Overall, the Brunei-Muara district recorded many cases, especially gastroenteritis, with the highest recorded in 2015 at 6819. Figure 6 shows an increasing trend throughout the years. This can be correlated with the number of leaks. As more leaks occur, the
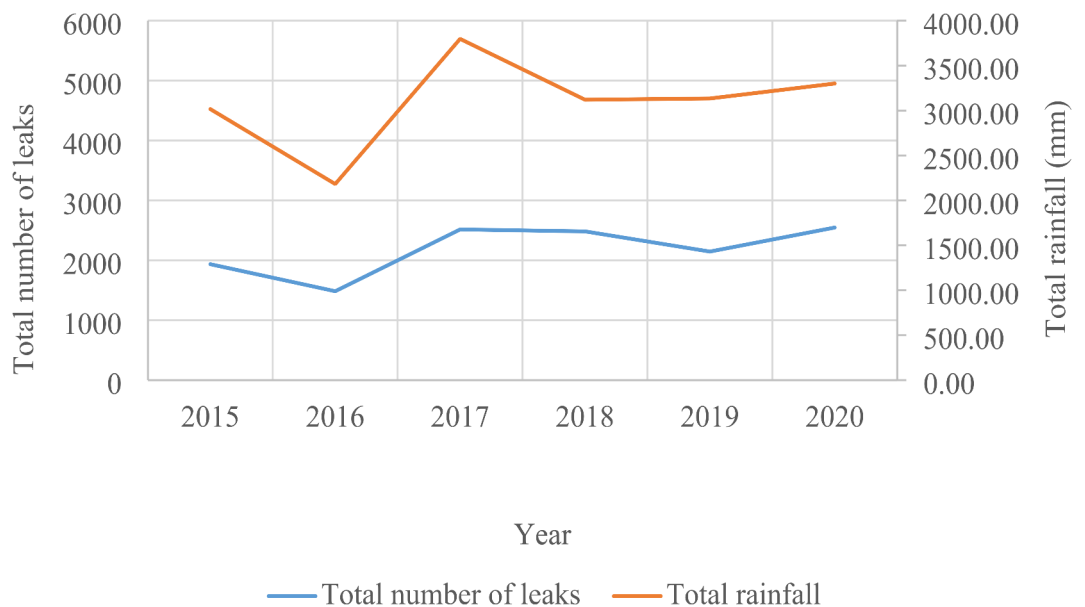

Fig. 5. Total number of leaks in comparison to rainfall.

District	Dysentery (Shigella)	Food Poisoning	Gastroenteritis	Hepatitis A	Para/Typhoid Fever	Salmonella Infection	Campylobacter Upsaliensis
BM	73	381	26,252	35	3	198	1
Tutong	2	51	2236	1	0	9	0
Kuala Belait	1	161	6323	2	4	16	0
Temburong	0	1	900	0	0	1	0

Table 6. Overall cases of Food and Waterborne diseases in Brunei Darussalam.
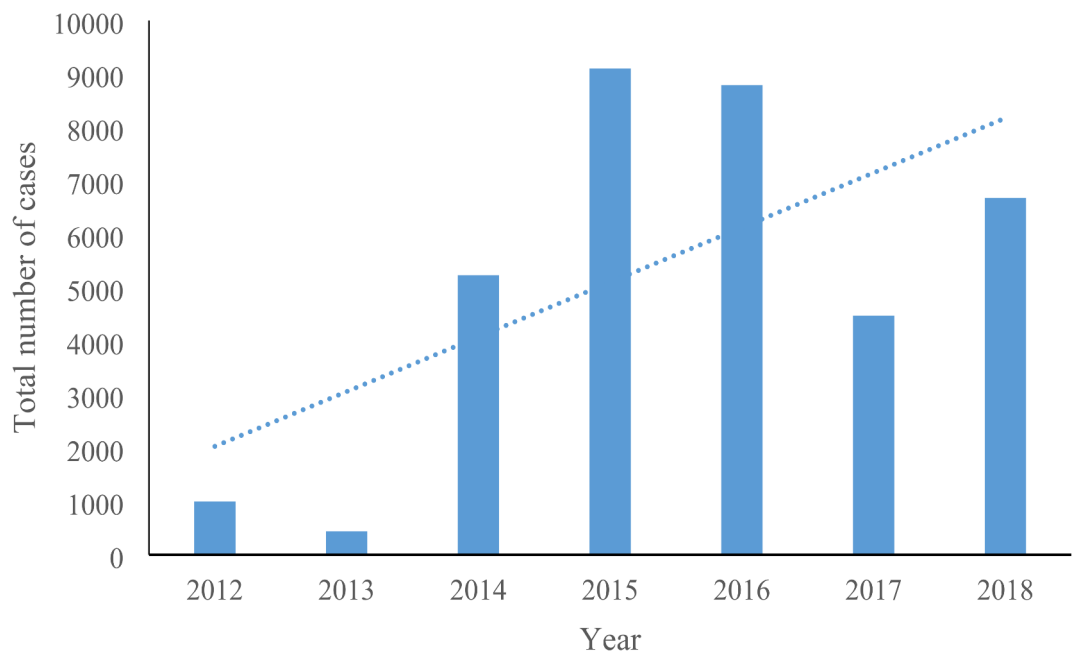
Fig. 6. Gastroenteritis in Brunei from 2012 to 2018.

more likely it is for the water supply to get contaminated and cause an outbreak of gastroenteritis. However, the source of the waterborne diseases cannot be determined following the areas of the zone since the dataset only provides cases based on districts.

Over the years, there have been increased cases of gastroenteritis, and the possible cause is water contamination. Additionally, the weather has been erratic, with heavy downpours followed by hot weather the next day, which may have affected the performance of the pipe, causing failures to occur and thus allowing contaminants to enter the pipeline.

The incidence rate of waterborne diseases is then calculated for Brunei-Muara district. Incidence rate is a measure of morbidity in which several new cases of a disease occur for some populations at the time[27–28]. First, the number of cases from 2012 to 2018 was divided by the number of populations according to the respective years. Then, the incidence rates were averaged at 0.0132, or 13 cases per 1000 people.

Due to the absence of water pipe network data, the exposed population cannot be calculated based on the buffered areas with a radius of 100 m around the leak points. Therefore, in this study, the exposed population is determined by multiplying the population with the incidence rate. Then, the percentage of the total exposed population in each zone was calculated to evaluate the risk to the exposed population. Based on the exposed population, zones D1, D2, D5, and D6 are considered high-risk zones. Zones D3, D4, and D8 are in a moderate range, whereas zone D7 is at low risk, as shown in Table 7.

Furthermore, the risk assessment was done by determining the probability of the severity of the health impact through the pipeline due to waterborne diseases. The risk assessment of the water supply is shown in Table 8. Then, a risk assessment map of the zones was produced based on the risk score achieved, as shown in Fig. 7. ArcGIS map was produced based on the risk classification. This map provides a foundational overview, allowing researchers and decision-makers to identify zones vulnerable to failure. These risk variables are colour-coded on a map to indicate high, medium, or low-risk areas.

Based on the evaluation, overall, zones D2 and D6 are deemed very high-risk, whereas zones D1, D3, D4, and D5 are high-risk zones, and D7 and D8 are moderate-risk zones.

The most low-lying areas are found in zones D2 and D6, and both zones have encountered the most average leaks per month. Thus, it can be deduced that floods play a major part in affecting the water supply pipes in the area. Therefore, there is a need to improve flood mitigation and control to manage the water pipeline in those areas. Regular monitoring should also be conducted. The data for pipe failures for pipe diameters ranging from

Zone	No. of Leaks	Population	Exposed Population	% of the Total Exposed Population	Evaluation of Exposed Population
D1	273	45,299	598	15.52%	High
D2	880	70,825	935	24.26%	High
D3	154	17,820	235	6.10%	Moderate
D4	181	18,839	249	6.45%	Moderate
D5	276	52,610	694	18.02%	High
D6	471	57,345	757	19.64%	High
D7	103	7945	105	2.72%	Low
D8	258	21,312	281	7.30%	Moderate

Table 7. Population exposed to contaminated water due to leaks.

Zone	Almost once a day	Almost once a week	Once a month	Once a year	Exposed Population	Weightage for severity in terms of Exposed Population	Risk Score	Evaluation
D1		0.8			High	0.8	0.64	High
D2	1				High	0.8	0.8	Very High
D3		0.8			Moderate	0.6	0.48	High
D4		0.8			Moderate	0.6	0.48	High
D5		0.8			High	0.8	0.64	High
D6	1				High	0.8	0.8	Very High
D7			0.6		Low	0.4	0.24	Moderate
D8			0.6		Moderate	0.6	0.36	Moderate

Table 8. Risk Assessment of zones in Brunei-Muara district.

2" up to 24" were obtained from DWS and were analysed using Excel. Based on the analysis, 60.62% of the pipe failures occurred for pipe size of 4", followed by 6" at 19.63% and 8" at 9.22%. About 96.35% are due to pipe leaks and 3.65% of the pipe failures are due to pipe burst. The high percentage of failure in 4" diameter pipe. It can be presumed that a 4" pipe size is unsuitable for water transmission. It can be observed that the bigger the diameter, the less likely it is to break; this may be due to the pipes being able to sustain the pressure acting on the pipes the bigger the size gets. Another reason for the high failure of a pipe size of 4" is probably because of the depth at which they are buried, and it could not resist the heavy loads. Figure 8 shows the pipe failure based on the diameter of the pipe.

It was discovered that 51.76% of pipe failures consist of ductile iron pipes, followed by 33.73% polyethylene, 6.55% asbestos cement, and 5.72% galvanised iron, as shown in Fig. 9. Based on the literature review, ductile iron pipes are used in the earliest days; therefore, this might be due to pipe aging and fluctuating weather conditions causing the soil to shrink and affecting the pipe in the ground. The pipe bursts that occurred throughout the years was caused by asbestos cement due to its rigid and inflexible structure. Heavy loads from roads or any pressure exerted on the pipes may have caused the pipes to break down. In the detection of leaks, a case study was done in Lambak Kanan by DWS, where they used District Metered Area (DMA) to detect leaks by installing flow and pressure sensors to examine the flow and pressure data for any irregularities that could potentially signify the existence of a leak in the network. These anomalies may encompass unforeseen decreases in pressure or a rise in flow rate, which can suggest pipe leakage. It is proposed to utilise variable-speed pumps and pressure-reducing valves to sustain optimal pressure as part of pressure management in pipeline systems to minimise leaks and employ digitalisation and advanced technologies such as GIS application, real-time water quality sensors, and real-time pressure monitoring integrated with SCADA systems to mitigate risks. Perform routine pipeline inspections and maintenance to identify and mitigate concerns promptly, employing non-invasive methods such as ground-penetrating radar (GPR) and implementing continuous monitoring technology like acoustic loggers or satellite-based systems.

This study is crucial for comprehending the possible hazards associated with pipe failures in several cities in developing nations and effectively allocating resources. By methodically evaluating these tangible hazards and applying suitable solutions to reduce their impact, operators of pipe network systems can improve the
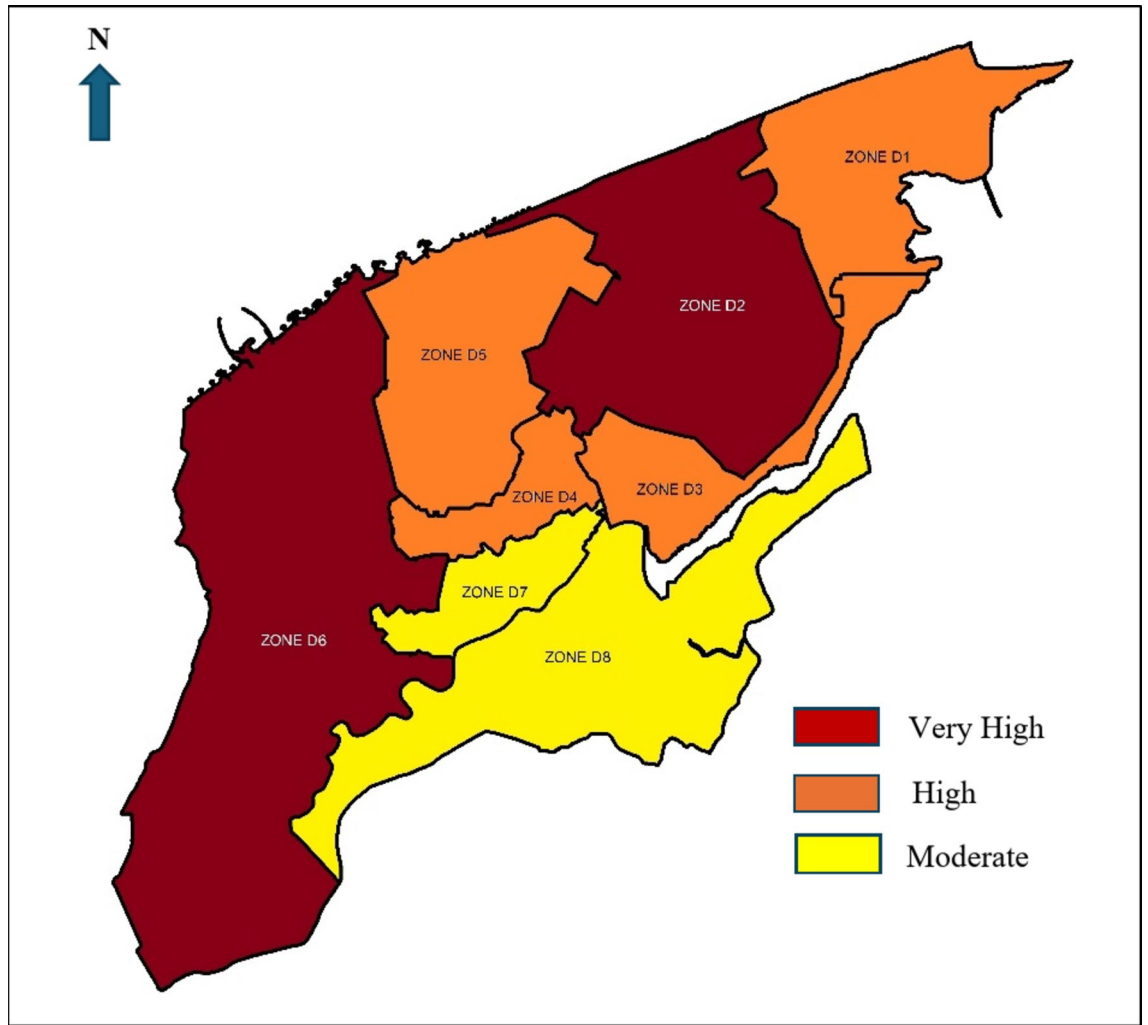
Fig. 7. Map of zones in Brunei-Muara district with the respective risk score.
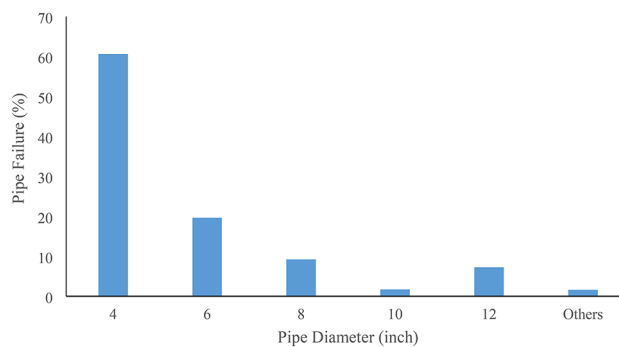

Fig. 8. Pipe failures based on the diameter of the pipe.

durability, longevity, and effectiveness of their infrastructure while minimising the likelihood of interruptions and malfunctions.

Conclusion

The risk assessment method of using a risk matrix and weightage is helpful for analysing risk for urban water supply. The risk was assessed based on the likelihood of leaks and the severity of their impacts on the exposed population. It was observed from the risk assessment map that Zone D2 and Zone D6 are at very high risk as they are located in flood-prone areas. Zones D1, D3, D4, and D5 are indicated as zones with high risk. Besides,
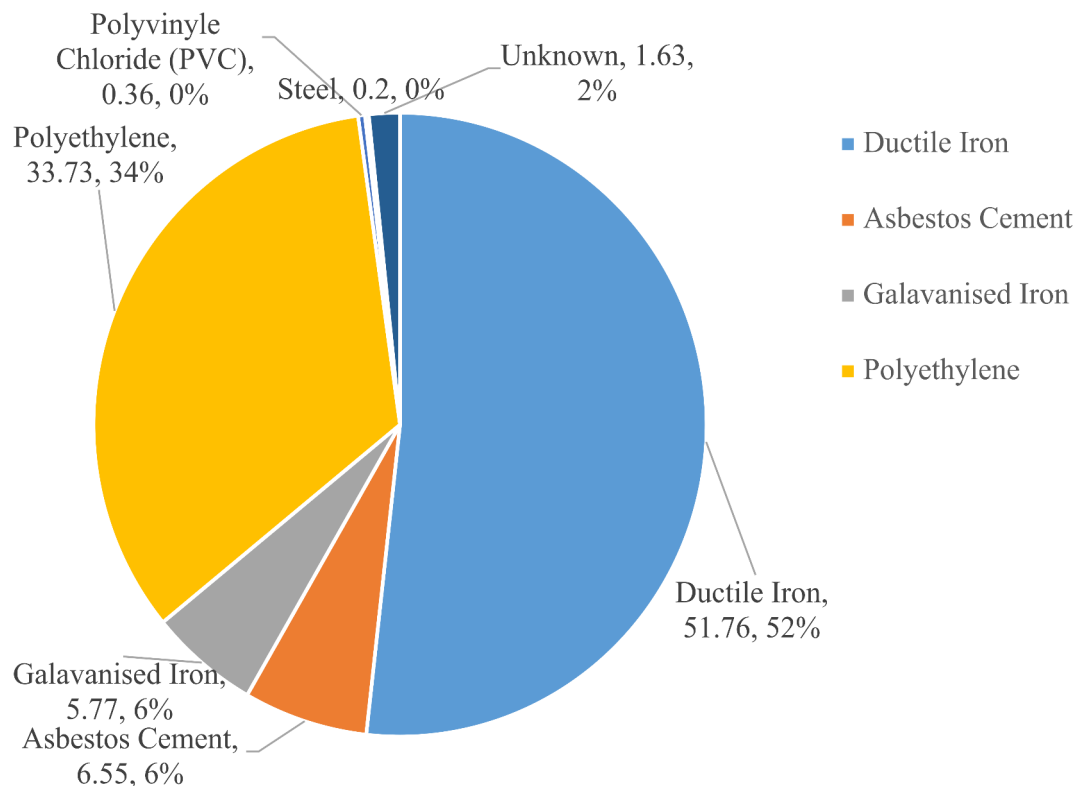
Fig. 9. Percentage of failure based on the types of pipes.

the pipe failures occurred more frequently in those areas due to topsoil erosion exposed by landslides and forest fires. Lastly, Zones D7 and D8 are at moderate risk as the pipe network system is relatively less aging. It is crucial for each zone in the pipe network system to accurately determine the points where operational activities and water-related risks coincide. It is recommended that DMA be performed all over the pipe network system in Brunei Darussalam as it can easily detect leaks and is a valuable tool for managing non-revenue water loss.

Furthermore, Brunei is actively exploring the adoption of digitalization by utilising advanced technologies such as data analytics, artificial intelligence (AI), and the Internet of Things (IoT) to establish an intelligent infrastructure for its pipe network system. Old 100 mm diameter pipes should be replaced with 150 mm bigger pipes made of PVC. Further studies should include the missing data such as pipe installation, pipe thickness, soil condition, potential traffic loads, etc.

Data availability
The datasets used and analyzed during the current study are available from the corresponding author upon reasonable request.

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Declarations

Competing interests

The authors declare no competing interests.

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