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Paul Daniel De Leon

engrpaulsy@gmail.com

Nueva Ecija University of Science and Technology

Michael John Villar

Nueva Ecija University of Science and Technology

Joeme Carl Demegillo

Nueva Ecija University of Science and Technology

Research Article

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Posted Date: November 18th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11443874/v1

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Additional Declarations: No competing interests reported.

Development of a Risk-Based Asset Management Framework for Water Distribution Pipe Replacement Prioritization in Aliaga Municipality, Nueva Ecija

Paul Daniel C. De Leon[1], Michael John M. Villar, Ph.D.[2], Joeme Carl Demegillo, Ph.D.[2]

[1] *Graduate Student, Master of Engineering Management, Nueva Ecija University of Science and Technology, Cabanatuan City, Nueva Ecija, Philippines*

[2] *Professor, Engineering Management Department, Nueva Ecija University of Science and Technology, Cabanatuan City, Nueva Ecija, Philippines*

Corresponding author: Paul Daniel De Leon
Email: engrpaulsy@gmail.com

ABSTRACT

This study developed a risk-based asset management framework for prioritizing water distribution pipe replacement in the water distribution system of Aliaga Municipality, Nueva Ecija. A two-stage quantitative case-study approach was used. Stage 1 screened 17 service areas using Area Asset Vulnerability (AAV) and Area Service Criticality (ASC). Stage 2 assessed the individual pipes within the selected areas using relative Likelihood of Failure (LoF), Consequence of Failure (CoF), and relative risk. Seven areas proceeded to Stage 2, where a total of 512 pipes were evaluated. The pipe-level CoF was based on the demand deficit obtained from individual pipe-unavailability simulations because the additional pressure-deficient-node indicator did not provide differences among the evaluated pipes. The final risk scores ranged from 2.50 to 25.00. A total of 116 pipe segments or 22.66% were classified as Very High risk, while 113 pipe segments or 22.07% were classified as High risk. Poblacion Area has the highest number of Priority 1 pipes, including all 18 pipes that obtained the maximum risk score of 25.00. Thus, the developed framework provides a practical basis for field verification and future pipe replacement planning even when historical pipe-failure records are not available.

Keywords: Asset Management, Water Distribution System, Likelihood of Failure, Consequence of Failure, Pipe Replacement Prioritization

1. THE PROBLEM AND ITS BACKGROUND

1.1 Background of the Study

Water distribution systems are important in providing adequate water supply to consumers at an acceptable pressure. The reliability of the system depends largely on the condition and performance of the pipelines that deliver water from the source to the different service areas. As these pipelines remain in operation for many years, their condition may change due to different physical and operating factors. Thus, water utilities need to identify which pipe sections require closer monitoring, rehabilitation, or possible replacement before their condition significantly affects the water service.

Pipe deterioration and failure may be affected by several factors such as pipe age, material, diameter, installation condition, operating pressure, surrounding environment, and previous performance. Barton et al. (2019) identified several factors that may contribute to the failure of drinking water pipelines. However, the influence of these factors may vary depending on the condition of a particular water distribution system. Hence, deciding which pipe should be replaced should not be based only on one factor such as age, diameter, or the presence of low pressure in the area. Forero-Ortiz et al. (2023) also showed that pipe-failure modelling commonly considers several

explanatory variables, since deterioration and failure cannot be represented by only one pipe characteristic.

Several methods have been developed to predict pipe failure and determine the condition of water distribution assets. Statistical pipe-failure models can provide useful information when sufficient historical records are available. Rifaai et al. (2022), for example, developed a pipe failure prediction and condition-scoring method using approximately 20 years of historical failure records. This type of analysis requires a complete and reliable record of previous pipe failures. However, not all water utilities have this kind of information. For water systems with limited records of leaks, breaks, and repairs, other approaches may be used. Phan et al. (2018), Salehi et al. (2022), and Nunes et al. (2023) showed that pipe assets can still be prioritized using available asset information, system characteristics, and engineering-based assessment even when complete failure records are not available.

One method that can be used is a risk-based approach. This approach considers not only the possibility that a pipe may fail but also what may happen to the water distribution system when that pipe becomes unavailable. This is commonly represented by the Likelihood of Failure (LoF) and the Consequence of Failure (CoF). Raspati et al. (2022) used failure probability together with hydraulic consequences in prioritizing the rehabilitation of water distribution networks. In the same manner, Phan et al. (2019) considered failure likelihood together with service disruption and hydraulic importance. D'Ercole et al. (2018) also used hydraulic simulation to assess the effect of individual pipe failures. Thus, pipes with similar physical characteristics may still have different levels of importance depending on how their failure affects the operation of the network.

The water distribution system in Aliaga Municipality, Nueva Ecija was previously assessed by De Leon and Demegillo (2026) using EPANET-JS. The hydraulic model consisted of approximately 82.83 kilometers of pipelines, 881 junction nodes, and five pumping stations. The previous study assessed the adequacy of the existing water distribution system and identified hydraulic deficiencies under existing and projected demand conditions. The results showed that hydraulic problems became more evident as water demand increased. However, the previous study focused mainly on the hydraulic adequacy of the system and did not determine which individual pipe sections should be given priority for replacement.

Hydraulic deficiency alone does not necessarily mean that a pipe should be replaced first. A pipe may experience low pressure because its diameter is no longer sufficient for the required demand, even if the pipe itself is relatively new. On the other hand, a pipe may perform adequately during normal operation but may still be critical when its failure or isolation affects a large portion of the distribution system. For this reason, the physical susceptibility of the pipe and the effect of its unavailability should be considered together when determining replacement priority.

The available records for the water distribution system in Aliaga Municipality do not contain a complete pipe-level history of leaks, breaks, and repairs. Due to this limitation, estimating an actual annual probability of failure for each pipe may not be practical. Thus, the present study used a relative LoF instead of an actual statistical probability of failure. A two-stage procedure was applied. Stage 1 conducted a preliminary area-level screening to identify service areas that required closer assessment. Stage 2 then evaluated the individual pipe segments within the selected priority areas using LoF and CoF. The resulting relative risk scores were used to classify and rank the pipes according to their replacement priority.

1.2 Objectives of the Study

The main objective of this study is to develop a risk-based asset management framework that can be used in prioritizing the replacement of water distribution pipes in Aliaga Municipality, Nueva Ecija. The framework will consider the both Likelihood of Failure (LoF) and Consequence of Failure (CoF) of the pipe assets.

Specifically, this research intends to:

A. characterize the existing water distribution pipelines and pinpoint the most critical service areas by preliminary area-level screening using selected asset, hydraulic, and service indicators;

B. assess the relative Likelihood of Failure and Consequence of Failure of the individual pipe segments within the selected priority areas and determine their corresponding risk levels; and

C. classify and rank the pipe segments based on their relative risk and determine their corresponding replacement priority.

1.3 Significance of the Study

This study may provide useful information to the Local Government Unit of Aliaga and the local water utility in identifying service areas and pipe sections that require greater attention. A reliable water distribution is important to households, businesses, and public facilities. Thus, knowing which pipe assets have higher relative risk may help in planning future rehabilitation, maintenance, and replacement activities.

The proposed framework may also be useful to other water utilities and water districts that have available pipe information and hydraulic models but have limited historical records of leaks, breaks, and repairs. In this kind of situation, developing a statistical pipe-failure model may not be practical. Hence, the use of preliminary area-level screening followed by detailed pipe-level assessment may provide a practical way of identifying priority areas and reducing the number of pipes that require more intensive hydraulic analysis.

Water resource planners and engineers may also use this study as a reference in comparing pipe assets using available physical, hydraulic, and service information. Instead of relying only on pipe age, diameter, or existing pressure condition, the framework also considers the possible effect when a pipe becomes unavailable. For this reason, the resulting priority may provide a better basis for determining which pipe sections require closer assessment. Water consumers may indirectly benefit through better identification of pipe sections that may have a greater effect on water service when failure occurs. Thus, the study may contribute to improving future water distribution planning and maintaining a more reliable service to consumers.

1.4 Scope and Limitations of the Study

This study focused on the water distribution pipe network in the Municipality of Aliaga, Nueva Ecija. The hydraulic model developed by De Leon and Demegillo (2026) served as the baseline model and was updated when necessary using available and verified network information. The model represented approximately 82.83 kilometers of pipelines, 881 junction nodes, and five pumping stations.

The study used a two-stage procedure in determining the relative replacement priority of the pipe assets. Stage 1 conducted a preliminary area-level screening using the pumping station DMA and the corresponding barangay or service-area coverage. This stage was used to identify the areas that required closer assessment. Stage 2 then evaluated the individual pipe segments located within the selected priority areas using relative LoF, CoF, and relative risk. Thus, the final replacement

priority was determined at the individual pipe level and not from the area-level screening alone. The study focused on the current or updated operating condition of the system.

The study was limited to the water distribution pipes included in the hydraulic model. Other assets such as pumping stations, wells, tanks, and valves were not assessed for replacement. However, these components remained part of the hydraulic model where they affected the behavior and operation of the water distribution system. The study ended with the classification and ranking of pipe segments based on their replacement priority. Detailed replacement design, project costing, life-cycle costing, economic analysis, budget allocation and implementation scheduling were not included.

The study was also limited by the available asset and failure records. Complete pipe-level historical records of leaks, breaks, and repairs were not available. Due to this limitation, LoF was treated as a relative index and not as an actual annual probability of pipe failure. Some information regarding exact installation dates, valve locations, service connections, and critical facilities was also limited. Hence, any indicators that didn't have information were left out of the final assessment. Pipe failure was represented in the hydraulic model by making one pipe segment unavailable at a time. This is a simplified representation of an actual field condition because the response to a real pipe failure may involve operational activities such as valve operations and pump adjustments. Thus, the resulting risk scores and replacement priorities represent relative priority and should still be supported by field verification and detailed engineering assessment before an actual pipe replacement decision is made.

2. METHODOLOGY

2.1 Research Design

This study used an applied quantitative case-study design to develop a risk-based asset management framework for water distribution pipe replacement prioritization in Aliaga Municipality, Nueva Ecija. Available pipe asset information and hydraulic simulation results were used to compare the relative susceptibility and service importance of the pipe assets within the distribution system.

The methodology followed a two-stage procedure. Stage 1 conducted a preliminary area-level screening to identify service areas that required closer assessment. Stage 2 then evaluated the individual pipe segments located within the selected priority areas using LoF and CoF. The first stage served only as a screening process and was not considered as the final replacement decision. Thus, the final pipe replacement priority was determined only after the detailed Stage 2 assessment. The overall procedure used in the study is shown in Figure 1

$$\text{Risk} = \text{LoF} \times \text{CoF}$$

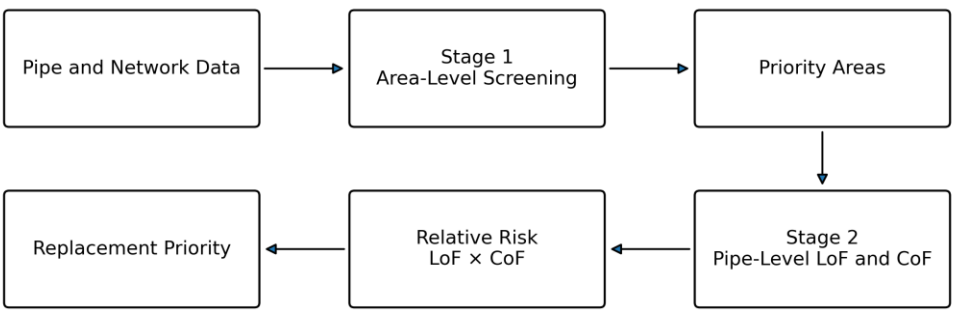


Figure 1. Two-stage risk-based asset management framework used in the study.

2.2 Study Area and Unit of Analysis

The study was conducted using the water distribution system in Aliaga Municipality, Nueva Ecija. The network is supplied through five pumping station DMAs: Sto. Rosario, San Juan, San Pablo, Bibiclat, and San Carlos. These service areas cover the barangays included in the existing distribution network.

The unit of analysis differed between the two stages. In Stage 1, the unit of analysis was the verified DMA or barangay-based service area used for preliminary screening. In Stage 2, the unit of analysis was the individual pipe segment represented in the hydraulic model. This distinction was necessary because Stage 1 reduced the number of areas that required detailed simulation, while Stage 2 determined the relative pipe risk and replacement priority.

2.3 Data Sources and Analytical Tools

The study mainly used existing local water utility records, geographic information, and data from the updated hydraulic model. Missing information was not assigned assumed values without a documented or technically reasonable basis. When available information was not sufficient to support a reliable score, the corresponding indicator was excluded from the final assessment. The data requirements used in the study and their corresponding sources are presented in Table 1.

Table 1. Data Requirements and Sources

Data	Primary Use	Source
Pipe ID and connectivity	Asset identification and pipe-level analysis	Hydraulic model
Pipe length	Asset characterization and area aggregation	Hydraulic model
Pipe diameter	LoF and asset characterization	Hydraulic model
Pipe material	Asset characterization	Local water utility records
Installation year or pipe age	LoF	Local water utility records
Node location and DMA/barangay area	Area screening and aggregation	Hydraulic model / GIS
Nodal demand	Area screening and CoF	Hydraulic model
Baseline pressure	Area screening and hydraulic analysis	Hydraulic simulation
Service connections	Area screening and CoF, if available	Local water utility records
Critical facilities	Area screening and CoF, if reliably linked	Local water utility / local records
Valve and isolation information	Pipe-unavailability simulation	Local water utility records

The main analytical tools used in the study were the existing EPANET-JS hydraulic model, Pressure-Driven Analysis (PDA), GIS or verified geographic information for service-area assignment, and spreadsheet-based calculations for scoring, aggregation, risk classification, and ranking.

2.4 Data Collection and Analytical Procedure

2.4.1 Preparation of the Pipe and Area Database

A working database was prepared by combining pipe records, node information, hydraulic-model data, and verified geographic service-area information. Each pipe retained its original identification from the hydraulic model together with the available asset information required for the analysis.

For the area-level screening, pipes and nodes were assigned to their corresponding pumping station DMA and barangay coverage. The documented pipe-laying periods were used as the basis for estimating pipe age when an exact installation year was not available. Where a pipe section had been replaced and a more recent verified replacement year was available, the replacement year was used. The documented pipe-laying periods and corresponding barangay coverage for each pumping station DMA are presented in Table 2.

Table 2. Pipe-Laying Period and Barangay Coverage by Pumping Station DMA

Pumping Station DMA	Pipe-Laying Period	Barangay Coverage
Sto. Rosario PS DMA	2003-2004	Poblacion areas, La Purisima, San Eustacio, Sto. Rosario, Magsaysay, and Santiago
San Juan PS DMA	2005-2006; 2022**	San Juan, San Felipe, and Umangan**
San Pablo PS DMA	2007-2008	San Pablo, Sto. Tomas, Macabucod, and San Emiliano
Bibiclat PS DMA	2009-2010	Bibiclat, Bucot, and Pantoc
San Carlos PS DMA	2021	San Carlos, Sunson, and Betes

Pipe sections in Umangan that were replaced under the verified 2022 TPR work were assigned the 2022 replacement year when the affected hydraulic-model pipe segments could be identified. This prevented recently replaced pipes from being scored using the older 2005-2006 San Juan DMA installation period. For San Carlos, the available 2021 installation period was used based on the verified network information applied in the study.

2.4.2 Stage 1: Preliminary Area-Level Screening

Stage 1 was used to identify which service areas required detailed pipe-level assessment. Two screening measures were used: Area Asset Vulnerability (AAV) and Area Service Criticality (ASC). These measures were used only for preliminary screening and did not replace the pipe-level LoF and CoF assessment in Stage 2.

Area Asset Vulnerability represented the general susceptibility of the pipe assets within each screening area using the available asset indicators. Since pipe material was the same throughout the network, material remained descriptive and was not used to distinguish vulnerability. Pipe age and diameter were used as the main asset-based screening information.

$$AAV_a = \Sigma(L_i \times S_i) / \Sigma L_i$$

where:
AAV_a = *Area Asset Vulnerability score of area a;*
L_i = *length of pipe i within the area; and*
S_i = *preliminary susceptibility score of pipe i.*

Area Service Criticality represented the relative service importance and baseline hydraulic vulnerability of each screening area. The retained indicators were total water demand, active service connections, and the percentage of nodes below the adopted service-pressure criterion. Critical facilities were not included in the final scoring because reliable linkage to individual areas and pipes was not available. Each retained indicator was converted to a common five-point scale. The five-point interpretation used for the area screening scores is presented in Table 3.

Table 3. Area Screening Score Interpretation

Score	Screening Interpretation
1	Very Low
2	Low
3	Moderate
4	High
5	Very High

The Area Screening Index (ASI) was calculated by combining AAV and ASC. Areas with higher ASI values were considered to require closer assessment. Areas classified as High and Very High proceeded to Stage 2. The category boundaries were established after the actual screening-score distribution was examined.

$$ASI_a = AAV_a \times ASC_a$$

where:
ASI_a = *Area Screening Index of area a;*
AAV_a = *Area Asset Vulnerability score; and*
ASC_a = *Area Service Criticality score.*

2.4.3 Stage 2: Pipe-Level Likelihood of Failure Assessment

Individual pipe segments within the selected priority areas were assessed for relative LoF. Since a complete historical record of pipe breaks and repairs was not available, the study did not estimate the actual probability of pipe failure. Instead, LoF was used to compare the relative failure susceptibility of pipes using asset information that could be supported by the available records.

All distribution pipes included in the study were uPVC. Pipe material was therefore not used as a LoF scoring indicator because it did not vary among the assets. The LoF assessment used pipe age and pipe diameter as the main scoring indicators. Hence, the resulting LoF values represented relative susceptibility within the Aliaga water distribution system and were not interpreted as actual failure probabilities. The interpretation of the relative LoF scores is presented in Table 4, while the corresponding pipe age and diameter scoring criteria are shown in Table 5.

Table 4. Relative Likelihood of Failure Interpretation

Score	Relative Likelihood of Failure
1	Very Low
2	Low
3	Moderate
4	High
5	Very High

Table 5. LoF Scoring Criteria for the Water Distribution System in Aliaga Municipality

LoF Indicator	Score 1	Score 2	Score 3	Score 4	Score 5
Pipe age / laying period	2021 or later	2009-2010	2007-2008	2005-2006	2003-2004
Pipe diameter	150 mm	100 mm	75 mm	50 mm	25 mm*

*The 25-mm category was retained only when the pipes were verified as distribution assets included in the hydraulic model and replacement-prioritization analysis.

$$LoF_i = (S_{(}Age,i_{)} + S_{(}Diameter,i_{)}) / 2$$

where:
LoF_i = *relative Likelihood of Failure score of pipe i;*
$S_{(}Age,i_{)}$ = *age score of pipe i; and*
$S_{(}Diameter,i_{)}$ = *diameter score of pipe i.*

2.4.4 Stage 2: Pipe-Level Consequence of Failure Assessment

The Consequence of Failure assessment determined the relative effect of a selected pipe becoming unavailable. A baseline simulation was first used to establish the reference pressure, required demand, and delivered demand of the updated network. Each candidate pipe within the selected priority areas was then represented as unavailable one at a time, after which the hydraulic simulation was repeated.

Pressure-Driven Analysis was used so that delivered demand could decrease when the available pressure became insufficient. The initial consequence indicators considered were percentage demand deficit, percentage of demand nodes below the required service pressure, affected service connections, and critical facilities. However, only indicators supported by reliable and differentiating information were retained in the final CoF scoring.

$$Ddef = Dreq - Ddel$$

$$Ddef,\% = [(Dreq - Ddel) / Dreq] \times 100$$

$$Ndef,\% = (Ndef / Ntotal) \times 100$$

where:
Ddef = *demand deficit;*
Dreq = *required demand;*
Ddel = *delivered demand during the pipe-unavailability condition;*
Ndef = *number of demand nodes below the adopted required/service pressure; and*
Ntotal = *total number of demand nodes evaluated.*

The Pressure-Driven Analysis used a minimum pressure of 5 psi, a required or service pressure of 16 psi, and a pressure-demand exponent of 0.50. The same hydraulic criteria were applied in the baseline and individual pipe-unavailability simulations.

The retained consequence results were converted to a common five-point scale after the distribution of the simulation results was examined. The original procedure allowed the CoF score to be calculated from the mean of the retained consequence indicators. However, the final simulations showed that the additional pressure-deficient-node indicator did not differentiate the evaluated pipes, while reliable pipe-specific service-connection and critical-facility information was not available. Thus, demand deficit percentage was retained as the final CoF scoring indicator. The five-point interpretation used for CoF is presented in Table 6.

$$CoF_i = \Sigma C_{ik} / m$$

where:
CoF_i = *Consequence of Failure score of pipe i;*
C_{ik} = *consequence score of pipe i for indicator k; and*
m = *number of retained consequence indicators.*

Table 6. Consequence of Failure Interpretation

Score	Consequence of Failure
1	Very Low
2	Low
3	Moderate
4	High
5	Very High

2.4.5 Relative Risk and Pipe Replacement Priority

The final relative risk score of each pipe was determined by combining its LoF and CoF scores. This allowed pipes with different physical characteristics and service effects to be compared using one relative risk value.

$$R_i = LoF_i \times CoF_i$$

where:
R_i = *relative risk score of pipe i;*
LoF_i = *Likelihood of Failure score of pipe i; and*
CoF_i = *Consequence of Failure score of pipe i.*

With LoF and CoF expressed on a scale from 1 to 5, the theoretical risk score ranged from 1 to 25. The following ranges were adopted for relative prioritization within the water distribution system in Aliaga Municipality. These ranges were used only for this study and were not treated as universal pipe-failure thresholds. The adopted relative risk classes and their corresponding replacement priorities are presented in Table 7.

Table 7. Relative Risk Classification and Replacement Priority

Risk Score	Risk Classification	Replacement Priority
1.00-4.00	Very Low	Priority 5
>4.00-8.00	Low	Priority 4
>8.00-12.00	Moderate	Priority 3
>12.00-16.00	High	Priority 2
>16.00-25.00	Very High	Priority 1

A higher risk score indicated a greater relative priority for further assessment and possible replacement. However, a pipe classified as High or Very High was not automatically recommended for immediate replacement. Field verification and detailed engineering evaluation are still needed before an actual replacement decision is made.

2.5 Statistical and Analytical Treatment

Descriptive statistics were used to summarize the pipe characteristics and the results of the different stages of the analysis. Frequency distributions and percentages were used to describe the area-screening classifications, LoF and CoF results, and final risk categories.

Arithmetic means were used to combine equally weighted indicator scores where applicable. For the area-level screening, length-weighted averaging was used to combine the susceptibility scores of the pipes within each screening area. Relative pipe risk was calculated by multiplying LoF and CoF. The resulting values were then classified and ranked according to relative replacement priority.

2.6 Current Network Design of the Locale

The existing hydraulic model for the water distribution system in Aliaga Municipality represents approximately 82.83 kilometers of pipelines, 881 junction nodes, and five pumping stations. The distribution system is divided into the Sto. Rosario, San Juan, San Pablo, Bibiclat, and San Carlos pumping station DMAs. These DMAs cover the barangays identified in Table 2.

The distribution pipes are uPVC with diameters ranging from approximately 25 mm to 150 mm. The 150-mm pipes are mainly located along the Sto. Rosario trunk line and in the San Carlos area. Most other trunk lines use 100-mm pipes, while the distribution branches generally use 75-mm and 50-mm pipes. The 25-mm pipes were included in the detailed prioritization only when they were confirmed as modeled distribution assets rather than individual service connections.

The hydraulic model was updated where verified network or operating information differed from the previous representation. The updated model then served as the hydraulic basis for the baseline condition, the area-level service indicators, and the Stage 2 pipe-unavailability simulations.

3. RESULTS AND DISCUSSION

3.1 Existing Pipe Characteristics and Area-Level Screening

The existing water distribution system in Aliaga Municipality is composed of uPVC distribution pipes represented in the hydraulic model. Pipe diameters range from approximately 25 mm to 150 mm. The 150-mm pipes are mainly located along the Sto. Rosario trunk line and in the San Carlos area, while most other trunk lines use 100-mm pipes and the distribution branches generally use 75-mm and 50-mm pipes. The available installation information also shows different pipe-laying periods among the pumping-station DMAs, ranging from 2003-2004 in the Sto. Rosario PS DMA to 2021 in the San Carlos PS DMA. These characteristics served as the physical basis for the preliminary asset assessment and the pipe-level LoF analysis.

The first stage evaluated the 17 screening areas using Area Asset Vulnerability (AAV) and Area Service Criticality (ASC). AAV represented the length-weighted preliminary susceptibility of the pipes within each area, while ASC represented the service importance and baseline hydraulic condition using total demand, active service connections, and pressure-deficient nodes. The Area Screening Index (ASI) was obtained by multiplying AAV and ASC. Thus, this stage was used only to identify which areas required a more detailed pipe-level assessment. The complete Stage 1 area-level screening results are presented in Table 8.

Table 8. Area-Level Screening Results

Screening Area	AAV	ASC	ASI	Classification	Stage 2
Poblacion	3.94	5.00	19.71	Very High	Yes
San Juan	3.45	4.33	14.95	Very High	Yes
Santiago	4.04	3.67	14.80	Very High	Yes
Bibiclat	2.94	5.00	14.69	Very High	Yes
Bucot	3.11	4.67	14.50	High	Yes
Sto. Tomas	3.25	4.33	14.09	High	Yes
San Felipe	3.35	4.00	13.40	High	Yes
Sto. Rosario	3.93	3.33	13.10	Moderate	No
San Pablo	3.00	4.33	13.00	Moderate	No
San Eustacio	4.25	3.00	12.74	Moderate	No
Magsaysay	4.15	3.00	12.44	Low	No
La Purisima	3.88	2.67	10.35	Low	No
San Emiliano	3.42	2.67	9.11	Low	No
Pantoc	3.83	2.33	8.93	Very Low	No
Macabucod	2.83	2.33	6.61	Very Low	No
San Carlos	1.68	3.33	5.60	Very Low	No
Umangan	1.60	2.33	3.74	Very Low	No

Poblacion obtained the highest ASI of 19.71. This was followed by San Juan with 14.95, Santiago with 14.80, Bibiclat with 14.69, Bucot with 14.50, Sto. Tomas with 14.09, and San Felipe with 13.40. These seven areas were classified as High or Very High based on the distribution of the ASI results and were selected for Stage 2. Thus, the preliminary screening reduced the detailed analysis from 17 screening areas to seven, equivalent to 41.18% of the original areas. The comparison of the ASI values for all screening areas is presented in Figure 2.

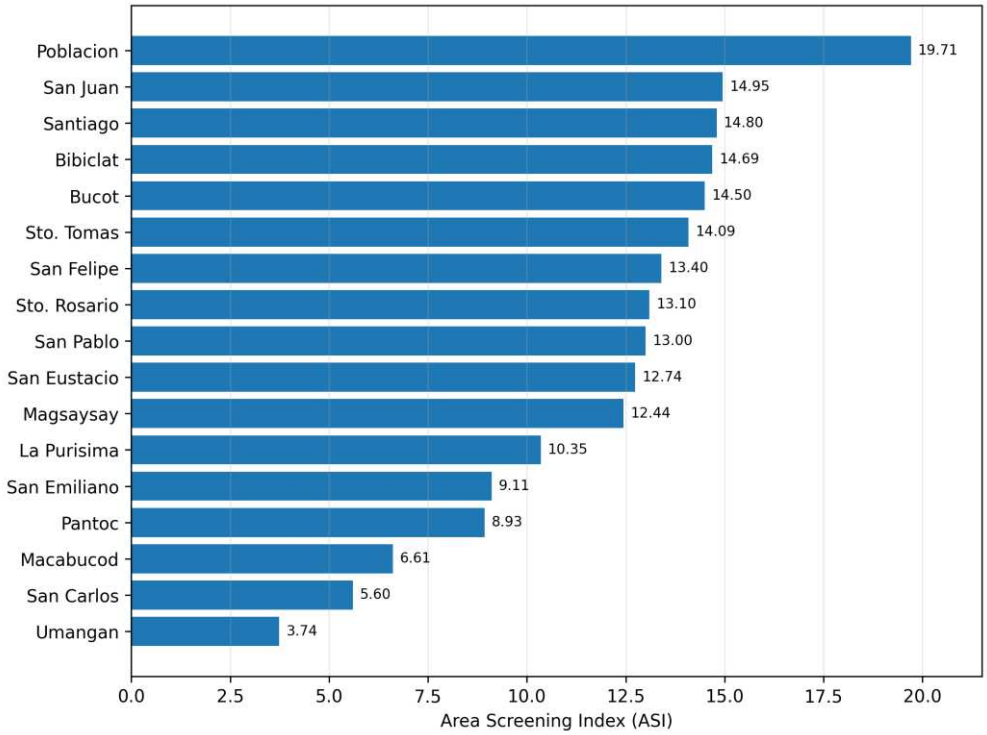


Figure 2. Area Screening Index (ASI) of the 17 screening areas.

The results show that area priority was not determined by asset vulnerability alone. The final screening result depended on the combined effect of pipe susceptibility and service criticality. For example, an area with relatively vulnerable pipes may still obtain a lower ASI when its service criticality is lower. On the other hand, an area serving a larger demand or a greater number of

service connections may obtain a higher screening priority. Hence, the first stage provided a more balanced basis for selecting the areas that required detailed pipe-level analysis.

3.2 Pipe-Level Likelihood and Consequence of Failure

A total of 512 pipes from the seven selected screening areas were included in the detailed Stage 2 analysis. The pipe-level LoF was determined using pipe age or laying period and pipe diameter. Since all distribution pipes included in the study were uPVC, material was retained only as an asset description and was not used as a scoring variable. The calculated LoF values ranged from 2.50 to 5.00. Higher LoF values generally represented older and smaller-diameter pipes, while lower values represented relatively newer and/or larger-diameter pipes. Due to the absence of complete pipe-level failure records, the LoF values were interpreted as comparative susceptibility scores and not as actual annual probabilities of failure.

The CoF was evaluated by making one selected pipe unavailable at a time in the pressure-driven hydraulic model. Under the baseline condition, the total required demand was 8.83 MLD and the delivered demand was also 8.83 MLD. A total of 875 demand nodes were evaluated. Of these, 750 nodes or 85.71% were already below the adopted service pressure of 16 psi even before an individual pipe was made unavailable.

For each pipe closure, the delivered demand was compared with the baseline required demand. The demand deficit and demand deficit percentage were calculated as follows:

$$D_{def,i} = D_{req} - D_{del,i}$$

$$D_{def,i,\%} = [(D_{req} - D_{del,i}) / D_{req}] \times 100$$

The number of pressure-deficient nodes was also compared with the baseline condition. However, the pipe-closure simulations did not cause an additional increase in the number of nodes below 16 psi. Thus, the additional pressure-deficient-node percentage was 0% for the evaluated closures. Since this indicator produced the same result and could not distinguish one pipe from another, it was excluded from the final CoF score. Affected service connections and critical-facility scores were also not included because reliable pipe-specific information was not available. For this reason, the final CoF classification was based on demand deficit percentage, which showed differences among the individual pipe-closure simulations. The relative CoF classification based on the demand-deficit results is presented in Table 9.

Table 9. Relative Consequence-of-Failure Classification

Demand Deficit (%)	CoF Score	Interpretation
<= 95.26	1	Very Low
>95.26 to 96.84	2	Low
>96.84 to 98.70	3	Moderate
>98.70 to 99.64	4	High
>99.64	5	Very High

The CoF limits were established from the distribution of the Stage 2 demand-deficit simulation results. Thus, the categories represent relative consequences among the pipes evaluated in the study. A pipe with a CoF score of 1 should not be interpreted as having an insignificant absolute service impact. It only means that its simulated consequence was lower when compared with the other pipes included in Stage 2. This is important because the demand-deficit percentages were generally high under the modeled pipe-unavailability conditions.

The differences in demand deficit among the individual pipe closures show that pipes within the same screening area do not necessarily have the same hydraulic importance. Their consequence depends on their location and their role in maintaining water delivery through the network. Hence, the Stage 2 simulation was able to identify pipe-level service effects that could not be determined from the area-level screening alone.

3.3 Relative Risk and Pipe Replacement Priority

The relative risk of each pipe was calculated by multiplying its LoF and CoF scores as follows:

$$Ri = LoFi \times CoFi$$

The resulting risk scores ranged from 2.50 to 25.00. Each pipe was then classified using the adopted risk ranges and assigned a corresponding replacement priority. The distribution of the 512 evaluated pipes is shown in Table 10.

Table 10. Distribution of Relative Risk and Replacement Priority

Risk Class	Risk Score	Replacement Priority	No. of Pipes	Percentage (%)
Very High	>16.00-25.00	Priority 1	116	22.66
High	>12.00-16.00	Priority 2	113	22.07
Moderate	>8.00-12.00	Priority 3	89	17.38
Low	>4.00-8.00	Priority 4	86	16.80
Very Low	1.00-4.00	Priority 5	108	21.09
		Total	512	100.00

A total of 116 pipes or 22.66% of the Stage 2 pipes were classified as Very High risk and assigned Priority 1. Another 113 pipes or 22.07% were classified as High risk and assigned Priority 2. Combined, 229 pipes or 44.73% of the evaluated pipes were included in the two highest replacement-priority groups. Figure 3 shows the distribution of the final risk classifications among the 512 evaluated pipe segments.

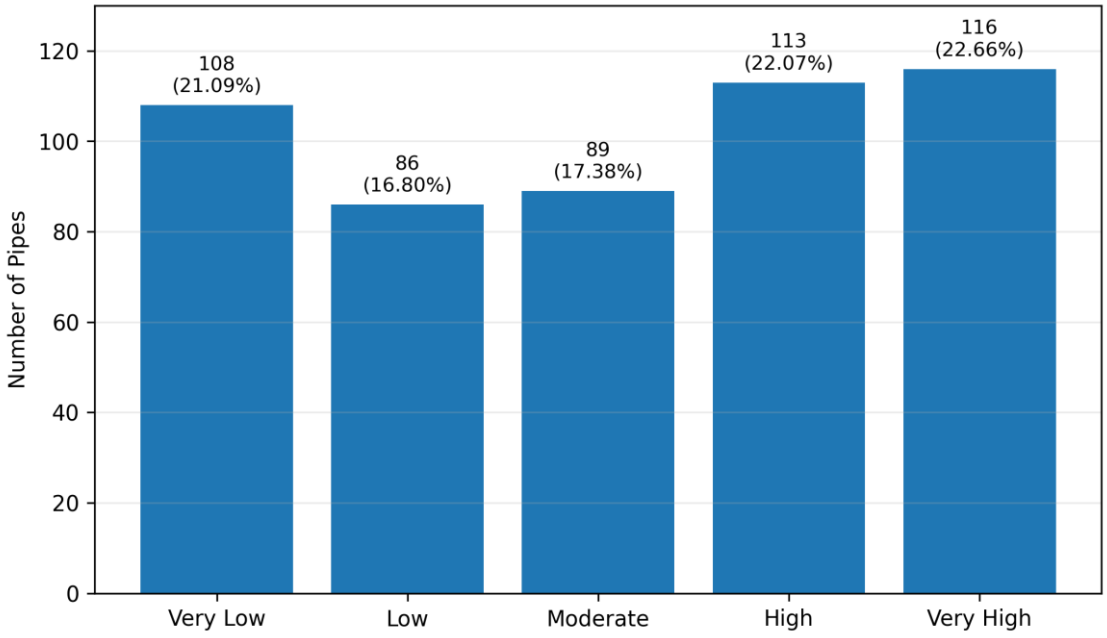


Figure 3. Distribution of final pipe risk classifications among the 512 evaluated pipes.

This result shows that the two-stage procedure did not automatically classify all pipes within a selected area as high priority. Instead, the final priority depended on the individual combination of LoF and CoF. The distribution of Priority 1 pipes among the seven selected screening areas is presented in Table 11.

Table 11. Distribution of Priority 1 Pipes by Screening Area

Screening Area	Pipes Evaluated	Priority 1 Pipes	Priority 1 within Area (%)
Bibiclat	108	19	17.59
Bucot	68	12	17.65
Poblacion	140	51	36.43
San Felipe	45	8	17.78
San Juan	71	11	15.49
Santiago	21	1	4.76
Sto. Tomas	59	14	23.73
Total	512	116	22.66

Poblacion contained the highest number of Priority 1 pipes. Of the 140 pipes evaluated in Poblacion, 51 were classified as Very High risk. This represents 36.43% of the evaluated pipes in Poblacion and approximately 43.97% of all Priority 1 pipes identified in Stage 2. This result is also consistent with Stage 1, where Poblacion obtained the highest ASI of 19.71. The distribution of Priority 1 pipes among the selected screening areas is shown in Figure 4.

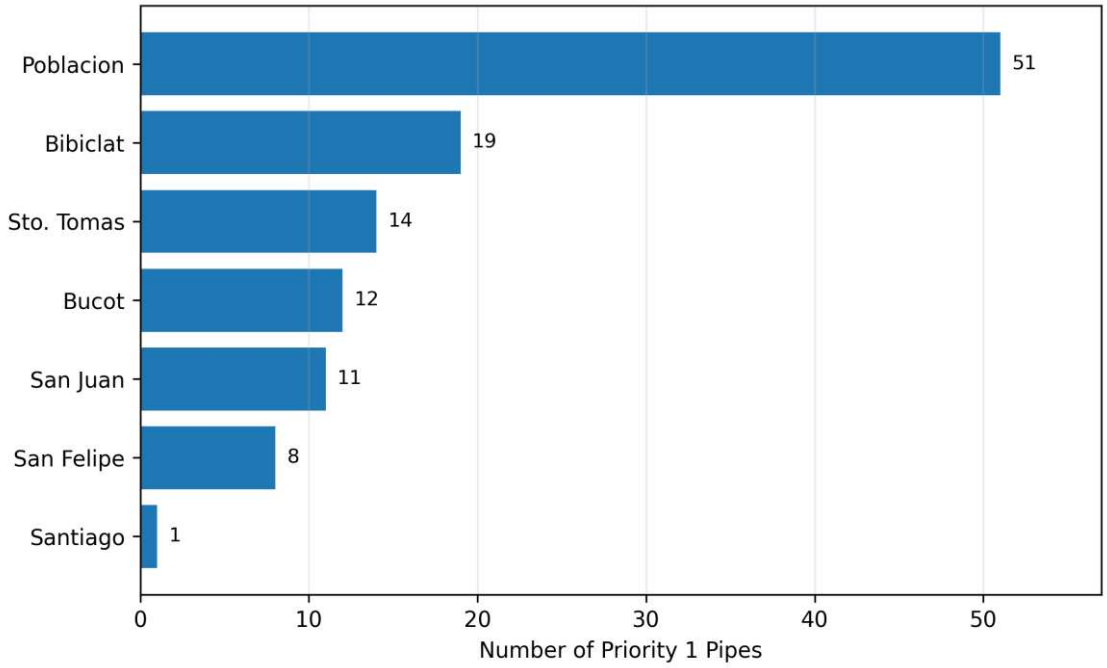


Figure 4. Distribution of Priority 1 pipes by screening area.

The maximum relative risk score was 25.00, which resulted from an LoF score of 5.00 and a CoF score of 5.00. Eighteen pipes obtained this maximum value, and all of them were located in Poblacion: POB14, POB16, POB17, POB18, POB44, POB46, POB47, POB93, POB94, POB123, POB124, POB125, POB132, POB136, POB137, POB140, POB141, and POB142. These pipes represent the highest relative replacement priorities under the developed framework because they combined the highest comparative failure susceptibility with the highest relative consequence of unavailability.

Several pipes obtained the same risk score and therefore received the same rank. This occurred because LoF and CoF were expressed using discrete scores. Hence, pipes with the same risk score were considered to have the same relative replacement priority under the present framework. If a unique implementation sequence is needed among tied pipes, other factors such as field condition, pipe length, accessibility, coordination with road works, and replacement cost may be considered during detailed engineering. These factors were outside the scope of the present study.

Overall, the two-stage framework reduced the assessment from area-level screening to individual pipe-level prioritization. Stage 1 identified the service areas that required detailed assessment, while Stage 2 distinguished the individual pipes according to their comparative susceptibility and modeled service consequence. Thus, the final risk ranking provides a systematic basis for identifying pipe sections that require greater attention for field verification and future replacement planning.

4. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

4.1 Summary of Findings

The study developed and applied a two-stage risk-based asset management framework for water distribution pipe replacement prioritization in Aliaga Municipality. Stage 1 used selected asset, hydraulic, and service indicators to screen the 17 service areas. Stage 2 then evaluated the individual pipe segments within the selected areas using relative LoF, CoF, and relative risk.

For the preliminary area-level screening, Poblacion obtained the highest ASI of 19.71. San Juan, Santiago, and Bibiclat were also classified as Very High, while Bucot, Sto. Tomas, and San Felipe were classified as High. These seven areas proceeded to Stage 2, reducing the detailed analysis to 41.18% of the original screening areas. Thus, the screening result showed that priority was affected by the combined asset vulnerability and service criticality of an area rather than by pipe characteristics alone.

A total of 512 pipes from the seven selected areas were evaluated in Stage 2. LoF scores ranged from 2.50 to 5.00 and were based on pipe age or laying period and pipe diameter. CoF was determined using individual pipe-unavailability simulations. Under the baseline condition, the model delivered the full 8.83 MLD required demand, although 750 of the 875 evaluated demand nodes were already below 16 psi. Since the number of pressure-deficient nodes did not increase during the pipe-closure simulations, the additional pressure-deficiency indicator did not distinguish the pipes and was excluded from the final CoF scoring. Hence, demand deficit percentage was used as the final comparative CoF indicator.

The final relative risk scores ranged from 2.50 to 25.00. Of the 512 evaluated pipes, 116 pipes or 22.66% were classified as Very High risk and assigned Priority 1, while 113 pipes or 22.07% were classified as High risk and assigned Priority 2. Thus, 229 pipes or 44.73% were included in the two highest replacement-priority groups. Poblacion had the highest number of Priority 1 pipes with 51, and all 18 pipes that obtained the maximum risk score of 25.00 were located in Poblacion.

4.2 Conclusions

Based on the findings of the study, the existing water distribution pipelines can be screened using available pipe characteristics together with hydraulic and service indicators even when complete historical failure records are not available. The preliminary area-level assessment identified seven High or Very High priority areas: Poblacion, San Juan, Santiago, Bibiclat, Bucot, Sto. Tomas, and San Felipe. These areas were selected for the detailed pipe-level evaluation. Thus, the area-screening stage was able to reduce the scope of the more intensive hydraulic consequence analysis.

The relative LoF and CoF assessment was also able to distinguish individual pipes within the selected areas. Pipe age or laying period and diameter provided a practical comparative LoF measure, while the pipe-unavailability simulations showed different effects on delivered demand. The additional pressure-deficient-node indicator did not provide differences among the pipes

because the baseline network already had 750 nodes below 16 psi and the evaluated closures did not increase this number. Hence, demand deficit percentage became the useful comparative hydraulic consequence indicator for the present analysis.

Combining LoF and CoF provided a clear relative pipe replacement-priority ranking. The framework identified 116 Priority 1 pipes and 113 Priority 2 pipes among the 512 evaluated pipe segments. Poblacion showed the greatest concentration of Very High risk pipes, including all 18 pipe segments with the maximum risk score of 25.00. Therefore, the developed framework provides a systematic basis for identifying pipe assets in Aliaga Municipality that should receive greater attention for field verification and future replacement planning.

4.3 Recommendations

Based on the results and limitations of the study, the local water utility may use the Priority 1 and Priority 2 results as an initial basis for field inspection and detailed engineering assessment. However, the ranking should not be considered as an automatic replacement order because the actual pipe condition, isolation feasibility, accessibility, and other field conditions still need to be verified. Thus, field verification should still be conducted before an actual pipe replacement decision is made.

The Priority 1 pipes in Poblacion, particularly the 18 pipes with a risk score of 25.00, should receive early field verification because they showed the highest combination of relative LoF and CoF. The other Priority 1 pipes in Bibiclat, Bucot, San Felipe, San Juan, Santiago, and Sto. Tomas should also be included in the verification program based on the resulting ranking. Hence, the ranking may serve as a guide in determining which pipe sections should be given greater attention first.

The existing baseline pressure condition should also be assessed separately from pipe replacement prioritization. Since 750 of the 875 evaluated demand nodes were already below the adopted 16-psi service pressure under the baseline condition, the possible system-wide hydraulic causes should be investigated. Due to this, operational or network improvements may be needed instead of considering all low-pressure locations as immediate pipe-replacement needs.

The local water utility should also improve and maintain pipe-level records such as installation dates, leaks, breaks, repairs, valve locations, service connections, and observed pipe condition. More complete records may allow future studies to develop failure-frequency or probability-based LoF models. For this reason, improving the available records may also improve the reliability of future asset-management and pipe-replacement decisions.

Future studies may also include pipe-specific affected service connections and critical facilities once reliable spatial linkage data become available. These indicators may provide additional information on the effect of pipe unavailability on consumers and important facilities. Thus, the consequence assessment may be improved by considering not only demand deficit but also the number and type of users that may be affected when a pipe becomes unavailable.

The framework may also be extended in future studies to include replacement cost, life-cycle costing, budget constraints, implementation scheduling, and economic analysis. These factors may be applied after the risk ranking to determine which projects can be implemented based on the available resources of the local water utility. Hence, the risk-based ranking may eventually be developed into a practical multi-year pipe replacement program.

Declarations

Funding Declaration
This research received no external funding.

Ethics, Consent to Participate, and Consent to Publish Declarations
Not applicable.

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Supplementary Files

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- ProcessingDatafortheRiskBasedAssetFramework.xlsx