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Decision-making for the hazard ranking of water distribution networks using the TOPSIS method

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ABSTRACT

Owing to the consecutive occurrence of water quality incidents, such as the black and red water situation in Incheon, Mullae (Seoul), and Pohang, as well as the tap water larval events in Incheon and Jeju in 2020, South Korea's Ministry of Environment announced the new addition of Article 12-2 of the Enforcement Decree of the Water Supply and Waterworks Installation Act 2021. Additionally, the importance of intensive management for vulnerable areas where water quality incidents and complaints may occur repeatedly was specified. Therefore, this study suggests the hazard ranking of district-metered areas in the study area using the deterioration of the water distribution network, complaints (water quality, leakage), and modeling results (water pressure, residual chlorine concentration) to support the establishment of a reasonable water distribution network maintenance plan. The effective and sustainable maintenance of the water distribution network is possible if the hazard ranking is regularly determined using the suggested methodology proposed herein and the water distribution network intensive management area is managed.

Key words: entropy weight, GIS, hazard ranking, TOPSIS method, water distribution networks

HIGHLIGHTS

- This study suggested a method to evaluate the hazard of water distribution networks and establish regional rankings from an engineering perspective.
- The data that can be accumulated in the water distribution network, such as the number of failures, water quality, and leakage complaints, were used.
- If the proposed methodology is used in establishing a network improvement and maintenance plan, the effective and sustainable maintenance of the water distribution network will be possible.

1. INTRODUCTION

Water supply facilities in South Korea witnessed dramatic growth via their association with the economic development of the 1970s, and the water supply pipelines intensively buried during this period should be examined, changed, or improved based on the 30-year durability period imposed by the Enforcement Decree of the Local Public Enterprises Act. Meanwhile, water supply pipelines buried before 1996 should be enhanced within the next ten years owing to the corresponding durable period cycle. Moreover, this proportion accounts for 34% of the total number of buried water supply pipelines. This aging scenario of water pipelines leads to significant water quality incidents that degrade supply services in water distribution networks. Some examples include the rust water incidents in Incheon Metropolitan City and Seoul in 2019 and the tap water larval events in Incheon and Jeju in 2020. Owing to these continual accidents, the need to manage the hazard ranking level that lowers the service level is constantly being raised. However, in the 2020 waterworks statistics, the reinvestment capacity for water distribution network management was 8.9% for metropolitan cities in South Korea, −10.4% for city-level local governments, and −23.3% for county-level local governments. Thus, there was a limit to continuously investing a budget and implementing improvement and maintenance. Furthermore, the inefficient input of such a limited budget causes water supply management to deteriorate and increases regional disparities in water supply services (MOE 2021).

Under this domestic situation, intensive water distribution network management was emphasized to reduce the regional gap in water supply services and efficient investment in limited budgets. Additionally, the Ministry of Environment has newly incorporated Article 12-2 in the Enforcement Decree of the Water Supply and Waterworks Installation Act 2021 (designation of areas for the priority management of waterworks networks, etc.) to specify the intensive control importance of the vulnerable regions where the degree of deterioration of waterworks networks, water quality accidents, and water quality complaints could occur repeatedly.

Accordingly, the recent provision in the Waterworks Act related to the designation of a priority management area for the waterworks network presented a legal and institutional basis for selection and concentration in operation and maintenance of the waterworks network. Nonetheless, the methodology of selecting a priority management area that comprehensively considers the aging issue of water distribution networks, water quality accidents, and water quality complaints still needs to be studied. Furthermore, decision-making while considering various variables as complexity increases owing to socioeconomic and environmental conditions is challenging (Yue *et al.* 2009).

Consequently, several studies have been published on hazard-based decision-making for effective operation and maintenance depending on the water distribution network aging situation. To manage the hazard ranking of water distribution networks, Ostfeld *et al.* (2002) undertook a reliability analysis study by topological reliability, a method to evaluate the physical connectivity between components in a system based on reliability evaluation, and a hydraulic method, an approach to assess supply quantity according to the water pressure at the nodes. Yazdani *et al.* (2011) developed a physical evaluation index based on pipe breakage history data and operational data that affected reliability and efficiency to improve the resilience of the water supply pipe network and established strategic pipe network operation and maintenance plans.

Dziedzic & Karney (2014) evaluate the water supply pipe network's reliability, vulnerability, and robustness via a scoring system, using an evaluation index that employs the quantity, hydraulic pressure data, and failure history data to secure the safety and sustainability of the water supply pipe network. Liserra *et al.* (2014) performed a reliability evaluation by considering the quantitative and water pressure and residual chlorine concentration evaluation indicators as indices of quantity and quality deriving from the aging water distribution network. Karamouz *et al.* (2016) conducted a reliability evaluation using pipe lifetime, failure history data, and hydraulic pressure data to efficiently manage water supply pipe networks. Accordingly, a decision-making plan was established for financial management plans depending on the remaining lifetime of the water pipe. Several previous studies have focused on decision-making using quantitative data such as water quantity and pressure. However, it is insufficient to comprehensively consider research on various factors, such as decision-making, using qualitative data, that is, data on civil complaints directly related to the service level of water supply and water distribution network aging specified in the relevant laws for the designation of areas for priority management, water quality accidents, and water quality complaints.

Therefore, this study aims to provide an engineering methodology for estimating the intensive hazard ranking management of waterworks networks based on the TOPSIS method by comprehensively using the following data as a case study: geographic information system (GIS) data of County Y as the research target area, water quality and leakage complaints for five years, and average operating water pressure and water quality data in district metered area (DMA) units derived from pipe network analysis. Through this, the present study intends to overcome the limitations of previous research and propose a rational decision-making support method considering the selection criteria of the water distribution network in the intensive management area stipulated by the law.

2. MATERIALS AND METHODS

Herein, evaluation items to appraise the risk of the water supply network are classified as follows: first, the failure hazard based on the probability of failure to consider safety; second, the water quality and leakage hazard based on the frequency of civil complaints to consider the service level; and third, the water pressure and water quality hazards based on hydraulic simulation modeling grounded in the pressure-driven analysis (PDA) to consider stability. Thereafter, the hazard ranking for the intensive management of the water distribution network was determined using the entropy–TOPSIS method. The schematic of the procedure of this study is depicted in Figure 1.

2.1. Study area

County Y, as the research target area, operates seven water purification plants and supplies tap water to an approximately 35,000 water supply population. The water distribution network in the study area is composed of 16 small DMAs. For the

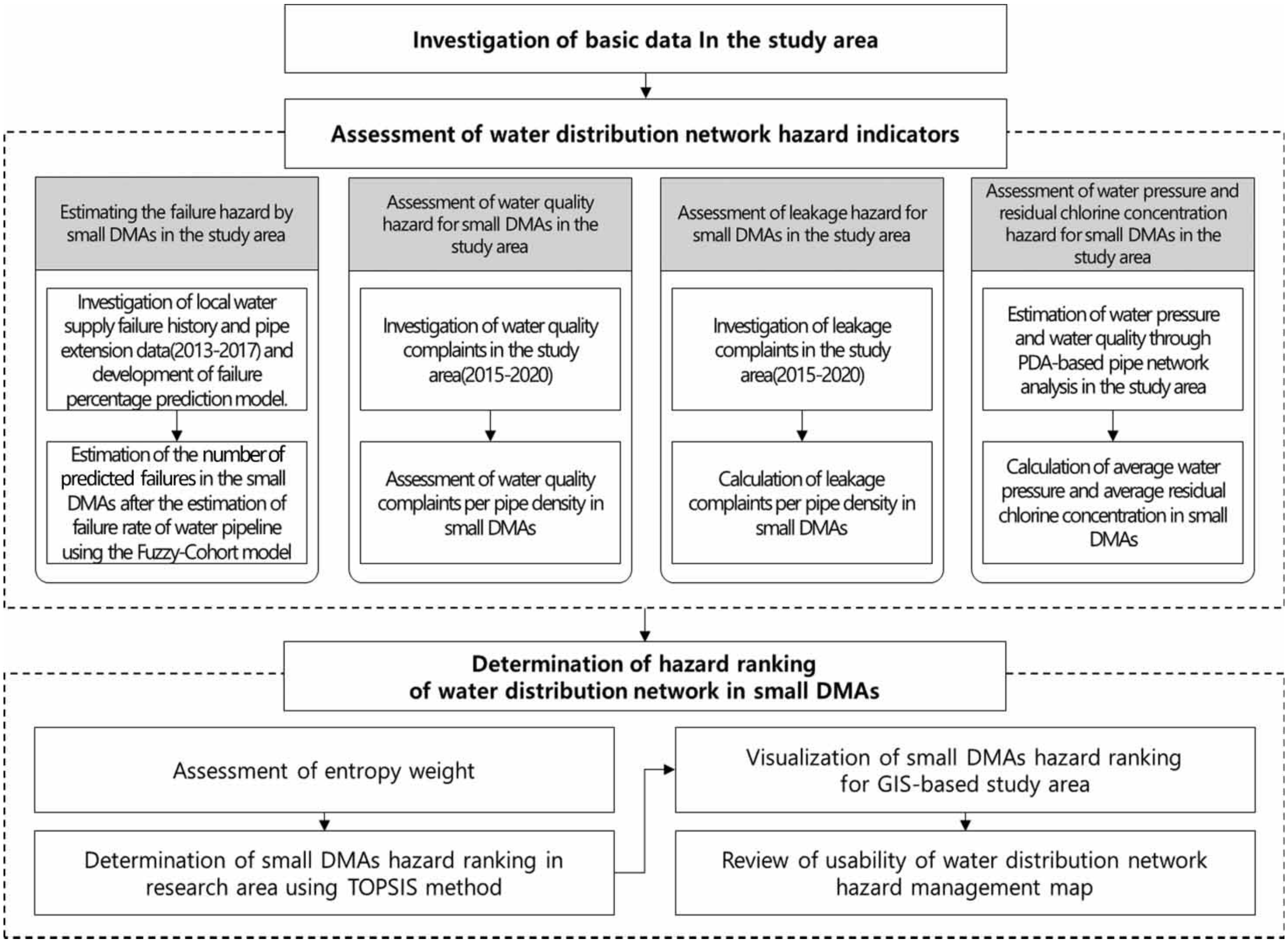


Figure 1 | Procedure for decision-making for hazard ranking in the water distribution network.

current water supply pipelines, the high hydrostatic pressure characteristics with high impact PVC pipe is 266,104 m, representing 35.40% of the total pipe extension, and the ductile cast iron pipe is 206,587 m, accounting for 27.48% of the total pipe extension. Figure 2 shows an overview of the water distribution network in the study area.

2.2. Estimation of entropy weight for the hazard ranking of water distribution networks

To apply the multi-criteria decision-making method, the weight value of the evaluation item to be appraised should be determined first. In the case of the analytic hierarchy process and Delphi techniques, which are generally used to determine weights, as they are subjective weight calculation methods, deviations could occur due to subjective factors (Li *et al.* 2011). Therefore, this study applies the objective and applicable information entropy-based weighting method proposed by Shannon (1948).

The entropy weight estimation method calculates the weight based on the concept of the intrinsic amount of information possessed by the evaluation item. After calculating the entropy depending on the variance based on the size distribution of the information attribute, the weight is derived by calculating the degree of diversity for each evaluation item.

Here, the decision matrix can be expressed as D in the equation below, and p_{ij} is the normalized result for all attribute values. At this time, the entropy of each property is called E_j, and the entropy is calculated according to the equation presented below. To obtain the weight of an attribute, the degree of diversity (d_j) is used, and it is calculated using the entropy of each attribute obtained above, and by normalizing these values for each attribute, the weight (w_j) of that attribute is derived. Therefore, in this study, the weights are derived through a mathematical calculation using the entropy method, and

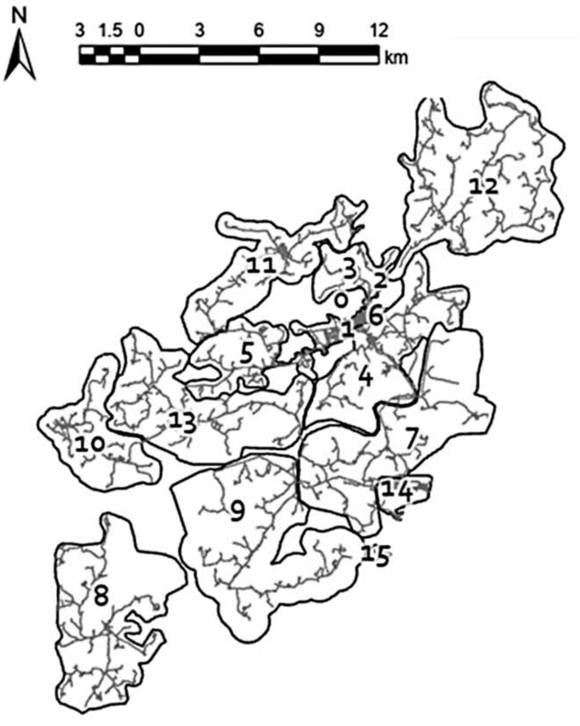


Figure 2 | Overview of the water distribution network in the study area.

the weight calculation procedure is presented as follows:

$$D = \begin{bmatrix} x_{11} & \cdots & x_{1j} & \cdots & x_{1n} \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ x_{i1} & \cdots & x_{ij} & \cdots & x_{in} \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ x_{m1} & & x_{mj} & & x_{mn} \end{bmatrix}$$

$$E_j = -k\sum_{i=1}^{m} p_{ij}\log p_{ij}\left(here,\ k = \frac{1}{\log\ m}; j = 1, 2, \ldots, n\right)$$

① $p_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} (i = 1, 2, \cdots, m;\ j = 1, 2, \cdots, n)$

② $d_i = 1 - E_j$

③ $w_j = \frac{d_j}{\sum_{j=1}^{n} d_j} (j = 1, 2, \cdots, n)$

According to the above-stated equation, the evaluation criteria with small information entropy are calculated to considerable weight, and the small information entropy indicates significant data uncertainty (Dos Santos *et al.* 2019).

2.3. Hazard ranking of water distribution networks based on the TOPSIS method

Several multi-criteria decision-making techniques are studied to support rational decision-making when various alternatives exist. First, in the case of the AHP, through pairwise criterion comparison, it is feasible to appraise the evaluation criteria quantitatively or qualitatively by classifying complex problems in a hierarchical structure. However, decision-making can be biased toward the subjectivity of experts, decision-making results can vary depending on the participating group, and when there are many alternatives to be compared in a complex decision-making matter, the number of pairwise criterion comparison evaluations increases drastically, which limits its application to decision-making matters with various standards and alternatives (Podvezko 2009).

Next, ELECTRE is a method derived from the concept of outranking and based on subjective information such as the preference function of the decision maker, in which alternatives that are difficult to compare are identified as comparable alternatives. However, there are limitations to this approach in that the weight of the evaluation criteria must be determined in advance, and the thresholds of the consistency and inconsistency indices used to determine the outranking of alternatives must be determined by the subjectivity of the researcher.

Furthermore, the weighted sum model is the most well-known and widely used method and has the advantage of a simple calculation process, but as this method is used under the assumption that the value of several attributes can be divided into the value of each attribute, it is inappropriate to apply this approach when the value of one attribute can increase or decrease the value of another attribute.

In this study, to resolve the uncertainty of depending on the subjectivity of experts who make decisions and to support decision-making that utilizes a large number of structured and unstructured data, the TOPSIS technique, which is easy to apply to complex decision-making matters with various criteria and alternatives, is applied in a reasonable way that simultaneously considers the best and worst alternatives. The TOPSIS method was first proposed by Hwang & Yoon (1981) as a decision-making approach under multi-criteria conditions. The TOPSIS method has excellent applicability with other decision-making techniques; thus, it is used in various fields to expand its concepts, such as hazard management, renewable energy, water resource management, and sustainability evaluation (Chen 2019).

This study adopts the TOPSIS method that supports decision-making by determining the ranking based on the distance scale to determine the hazard ranking of the water distribution network in the study area. The TOPSIS method consists of an ideal solution (IS) and a negative ideal solution (NIS). The best alternative is a solution close to the IS and farthest from the NIS when ranking according to the two solutions. The measure of distance is used as the Euclidean distance or city–DMA distance.

For TOPSIS analysis, the multi-criteria decision-making matrix should be normalized using the evaluation items previously selected for ranking. This is because the data of different units for each evaluation item should be converted into a dimensionless form and compared with the same scale. Vector normalization is mainly used when employing the TOPSIS method.

Therefore, this study constructed a vector normalization-based weighted normalization matrix using the entropy weights calculated earlier, and the closeness coefficient (CC) was estimated after calculating the IS and NIS to determine the ranking. In this case, the city–block distance was applied to consider the assumption that the closest alternative to the IS was the farthest from the NIS as a measure of the distance. The procedure for performing TOPSIS analysis is presented as follows:

① Structuring weighted normalization matrix

$$v_{ij} = \overline{x_{ij}} \times w_{ij},\ i = 1, 2, \cdots, m,\ j = 1, 2, \cdots, n$$

② Calculation of IS and NIS

$$v_j^+ = \{(max_j v_{ij} \text{ if } i \in I^+,\ min_j v_{ij} \text{ if } i \in I^-)\}$$

$$v_j^- = \{(min_j v_{ij} \text{ if } i \in I^+,\ max_j v_{ij} \text{ if } i \in I^-)\}$$

③ Measure the distance between IS and NIS for each alternative

$$S_j^+ = \sqrt{\sum_j (v_j^+ - v_{ij})^2},\ i = 1, 2, \cdots, m$$

$$S_i^- = \sqrt{\sum_j (v_j^- - v_{ij})^2},\ i = 1, 2, \cdots, m$$

④ Calculation of the closeness coefficient

$$CC_i = \frac{S_i^-}{S_i^+ + S_i^-},\ i = 1, 2, 3, \cdots, m$$

3. RESULTS AND DISCUSSION

3.1. Assessment results of DMA hazard depending on the hazard assessment indicators of water distribution networks

3.1.1. Assessment result of failure hazard

Previous studies that have estimated the future breakdown rate of water pipes have limitations in that they only consider the building age without comprehensively considering various environmental factors in which water pipes have been buried (Saegrov 2005; Kim *et al.* 2018; Bruaset *et al.* 2018). Therefore, this study used the fuzzy-cohort survival model developed in previous studies by Kim *et al.* (2019) that applied the fuzzy theory to evaluate failure hazards to replicate the failure trend of the study area by considering various characteristics, such as pipe lifetime of waterworks pipeline, pipe type, pipe diameter, above-road type, soil type, joining type, and burial depth.

For the failure hazard, each small DMA's expected failures per year were used as an index for each pipeline's failure probability. To consider the environmental factors of the water supply pipeline in the failure hazard assessment, the GIS data of the study area are used. The assessment result of the failure hazard is shown in Figure 3.

The higher the fuzzy score, which is a factor influencing the failure of the water supply pipe, the higher the frequency of failure and the quicker the failure is expected to occur. Using the fuzzy-cohort model, as a result of estimating the probability of failure to the supply and drain water pipelines in County Y based on the data collected in 2020 and calculating the annual number of failure predictions using the probability of failure, the most significant number of predicted failures (34.42 cases/yr) in small DMAs was established as belonging to small DMA 12.

3.1.2. Assessment results of hazards depending on water quality and leak complaints

As the small DMAs in the study area are different in scales, such as area, pipe extension, and quantity of water hydrants for each DMA, it is necessary to compare the number of civil complaints for each small DMA in consideration of the effect of the

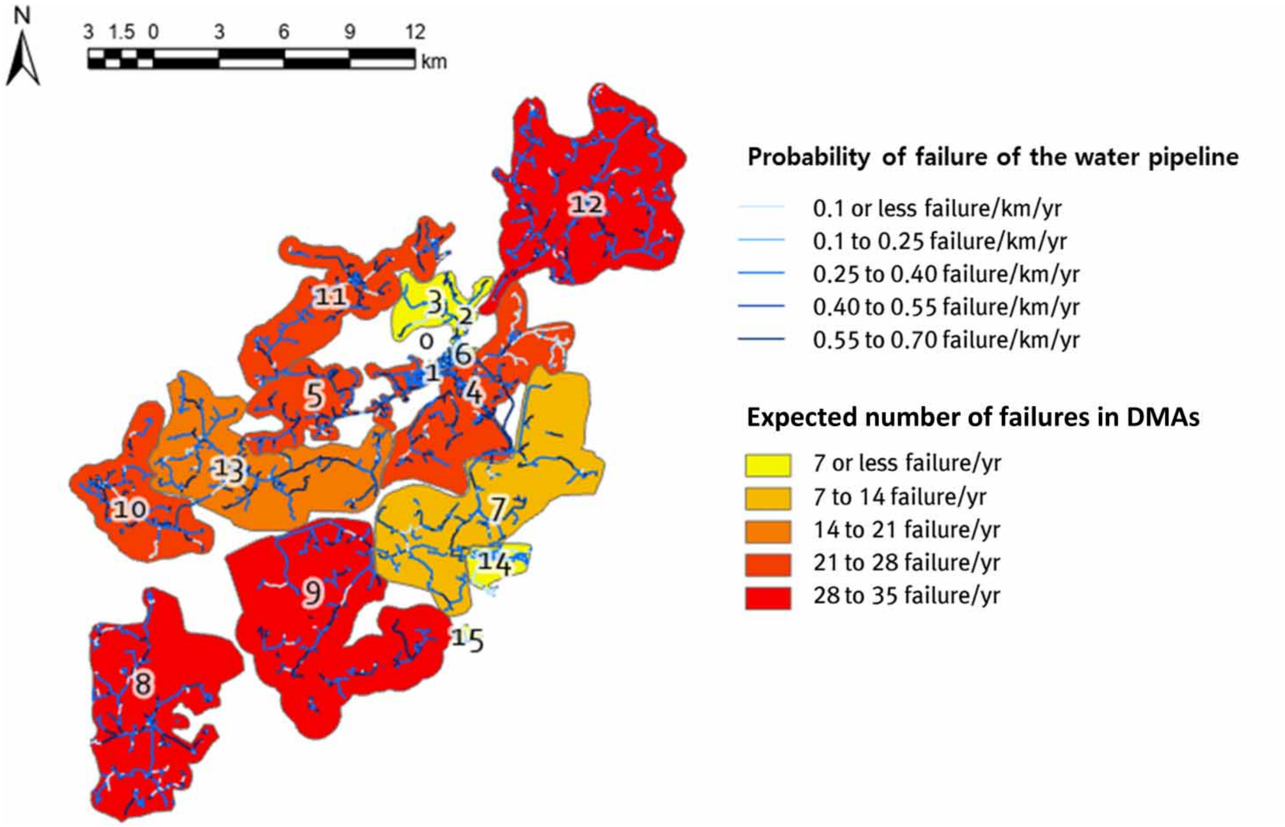


Figure 3 | Assessment result of failure hazard depending on the probability of failure.

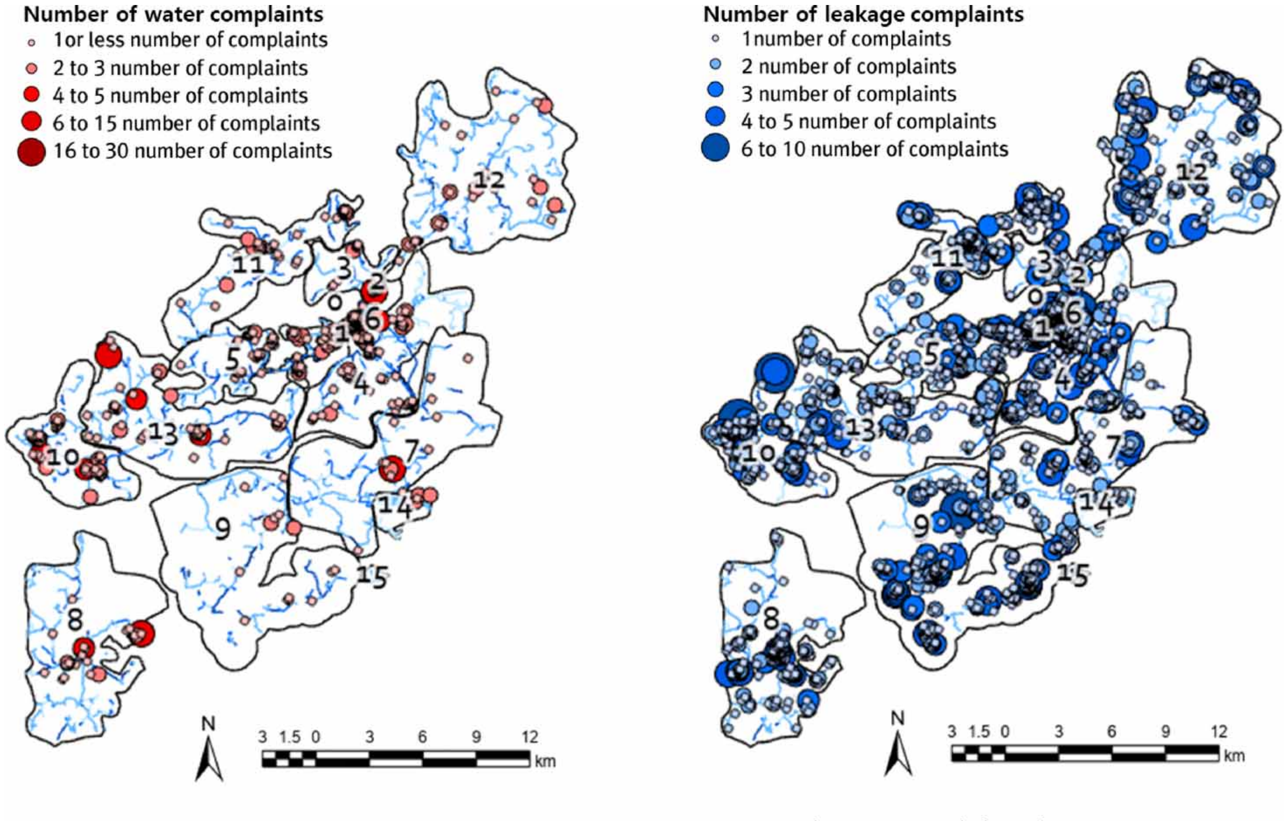
scale. Accordingly, the concept of pipe density divided by the pipe extension area was defined as a hazard index. The water quality complaints for five years (2015–2020) per small DMA pipe density in the study area are shown in Figure 4 using GIS. As a result of showing the water quality complaints that repeatedly occurred in the same area for five years, the analysis revealed that DMA 4 had the highest hazard, with 65.6767 cases/km/km^2 of water quality complaints per pipe density. In addition, the number of leak complaints per pipe density within a small DMA was found to be the highest in DMA 9, with 77.1372 cases/km/km^2.

3.1.3. Water pressure and assessment results of water quality hazard according to pipe network analysis

For the efficient operation of the waterworks network, proper water quantity, quality, and pressure corresponding to the demand must be maintained. In this study, a PDA-based hydraulic analysis was performed to consider the stability of water quality and pressure.

The hydraulic analysis of the waterworks network is largely classified into two types: the demand-driven analysis (DDA) technique, which performs the hydraulic analysis under the assumption that customer demand is always satisfied regardless of the water pressure of the entire system, and the PDA, which performs the hydraulic analysis under the assumption that customer demand varies depending on the water pressure of the entire system. Notably, DDA has no problem in interpreting the water distribution network if the water supply system maintains normal operating conditions, but if an unspecified amount of demand, such as fire or damage due to pipe aging, occurs, negative pressure is generated throughout the system, thereby limiting the hydraulic analysis performance. However, as PDA calculates the flow rate that can be supplied according to the pressure conditions at the nodes, it can overcome the limitations of models based on DDA when analyzing water distribution networks under abnormal operating conditions where unspecified demand occurs.

Therefore, in this study, hydraulic simulation results (water pressure, residual chlorine concentration) were derived through a hydraulic pressure-based analysis under the assumption that the demand of consumers varies depending on



Water quality complaints in DMAs

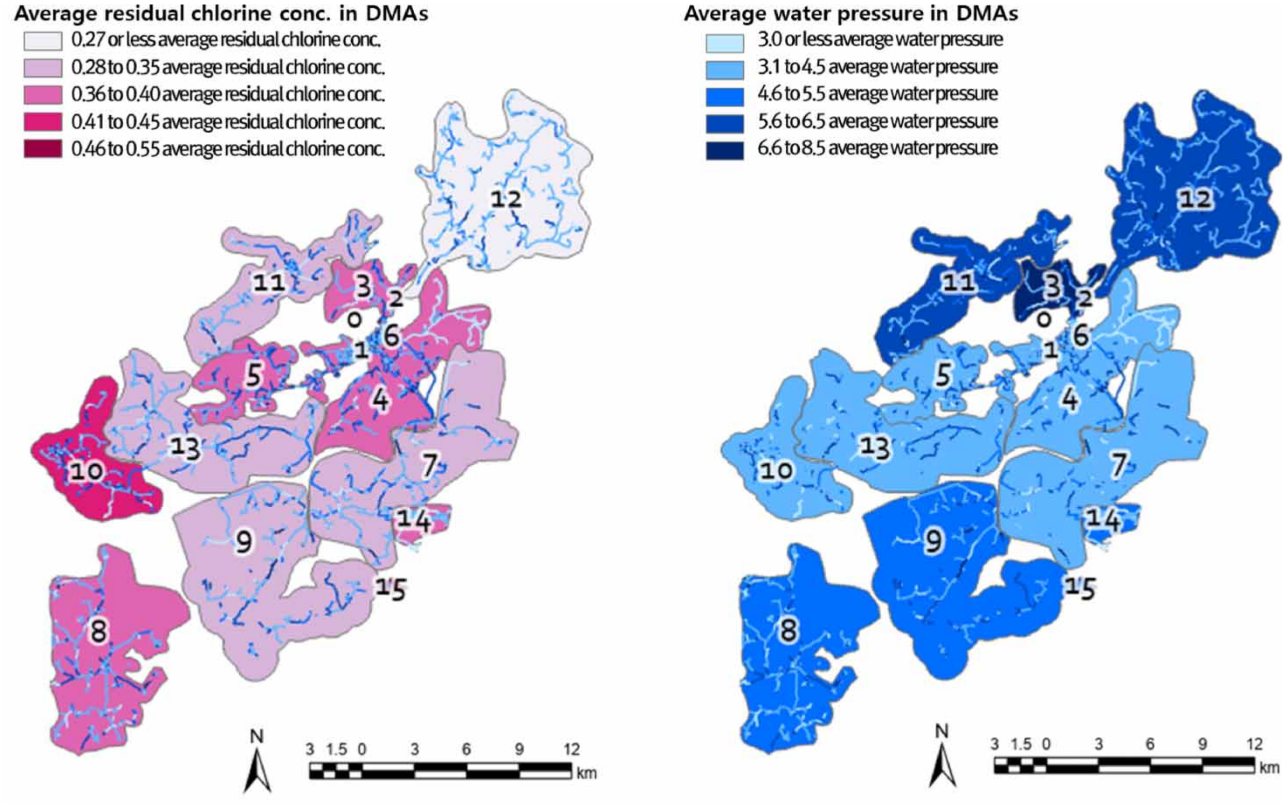
Leakage complaints in DMAs

Figure 4 | Assessment results of hazard depending on water quality and leak complaints.

the water pressure of the entire system and in connection with the risk of damage and civil complaint (water quality and leakage) evaluation indicators, and it was aimed to support the establishment of effective improvement plans by identifying DMAs with high risks in terms of the water quantity, water quality, and hydraulic pressure of the water distribution network.

Figure 5 shows the assessment results of water pressure and water quality hazard according to water distribution network analysis. As a result of the average operating water pressure analysis according to the hydraulic analysis of the time period with the highest water usage by the water usage pattern, DMA 3 was analyzed as a small DMA with the highest average water pressure in County Y with an average water pressure of 8.49 kgf/cm^2, while DMA 2 was analyzed as a small DMA with the lowest average water pressure with an average of 3.04 kgf/cm^2. It was found that the average water pressure of DMA 3 was out of the appropriate water pressure range, ranging from the minimum hydrostatic pressure of 1.53 kgf/cm^2 to the maximum hydrostatic pressure of 7.1 kgf/cm^2, as suggested by the Waterworks Design Standards (MOE 2017). In the case of the remaining DMAs, it was analyzed that they were operated within the appropriate operating water pressure range presented in the design standards for the waterworks facilities of South Korea.

Additionally, as a result of the average residual chlorine concentration analysis, the average residual chlorine concentration of DMA 0 indicated the highest value in County Y with 0.54 mg/L. Moreover, the average residual chlorine concentration of DMA 12 was 0.27 mg/L, which was analyzed as a small DMA with the lowest average concentration. As the residual chlorine concentration in the area is maintained at approximately 0.2–0.5 mg/L, it appears to be operated at a concentration that satisfies the residual chlorine concentration standard (0.1 mg/L or more and 4.0 mg/L or less) specified in the Waterworks Act.



Average residual chlorine concentration in the DMAs

Average water pressure in the DMAs

Figure 5 | Assessment results of water pressure and water quality hazard according to water distribution network analysis.

3.2. Decision-making for hazard ranking of the water distribution network

3.2.1. Result of entropy weight calculation

To select an intensive management area for the water distribution network in the study area by using the TOPSIS method, the weights of the hazard evaluation indicators, such as the number of failure predictions within a small DMA and the number of water quality and leak complaints per water pipe density should be estimated.

Accordingly, the hazard evaluation indicator weights were determined through a hydraulic calculation using the entropy technique. E_j, shown in Table 1, is the information entropy value calculated from the vector normalized evaluation item value, and d_j is the degree of diversity value; w_j is estimated using the calculated information entropy value and the degree of diversity value. As a result of the weight calculation, the weight of Criterion 2 was noted to have the most significant value of 0.3663.

Then, the weights of Criteria 3, 1, 4, and 5 were 0.3578, 0.2376, 0.0234, and 0.0150, respectively. Criterion 5 showed the smallest weight, which was believed to be the difference in data cohesion value caused by the variance deviation of the attribute values in the evaluation items.

3.2.2. The hazard ranking result of the water distribution network

Table 2 shows the results of calculating the solution and distance with the worst small DMA condition when the TOPSIS method has the worst state by applying the entropy weight to determine the hazard ranking of the water supply network in the study area.

Table 1 | Results of hazard evaluation indicator weights

Division		Criterion 1	Criterion 2	Criterion 3	Criterion 4	Criterion 5
Water distribution network hazard indicators		The number of predicted failures in DMAs (cases/km)	The number of complaints about quality per pipe density in DMAs (cases/km/km^2)	The number of complaints about leakage per pipe density in DMAs (cases/km/km^2)	Average water pressure in DMA (kgf/cm^2)	Average residual chlorine concentration in DMA (mg/L)
Entropy weight	E_j	0.8864	0.8249	0.8290	0.9888	0.9928
	d_j	0.1136	0.1751	0.1710	0.0112	0.0072
	w_j	0.2376	0.3663	0.3578	0.0234	0.0150

Table 2 | Results of water distribution network hazard ranking by the TOPSIS method in County Y

DMA	Criterion 1	Criterion 2	Criterion 3	Criterion 4	Criterion 5	Closeness coefficient	Hazard ranking
0	0.0183	0.0042	0.0085	0.0047	0.0051	0.9436	12
1	0.0190	0.0059	0.0085	0.0047	0.0048	0.9410	11
2	0.0115	0.0026	0.0050	0.0034	0.0046	0.9657	14
3	0.0189	0.0816	0.0279	0.0096	0.0036	0.7849	10
4	0.0768	0.2139	0.0942	0.0047	0.0037	0.5415	2
5	0.0752	0.1200	0.0828	0.0047	0.0035	0.6557	5
6	0.0037	0.0000	0.0009	0.0075	0.0038	0.9850	15
7	0.0366	0.0494	0.1124	0.0050	0.0028	0.7131	9
8	0.0918	0.0769	0.0964	0.0051	0.0034	0.6727	7
9	0.1036	0.1062	0.2232	0.0060	0.0028	0.5146	1
10	0.0676	0.1222	0.0778	0.0050	0.0041	0.6618	6
11	0.0783	0.0781	0.1000	0.0069	0.0029	0.6795	8
12	0.1012	0.0776	0.1330	0.0065	0.0025	0.6268	3
13	0.0455	0.1434	0.0764	0.0043	0.0031	0.6473	4
14	0.0127	0.0033	0.0015	0.0061	0.0036	0.9635	13
15	0.0012	0.0000	0.0015	0.0063	0.0043	0.9896	16

The CC value of DMA 9 (small DMA) was calculated at the minimum value of 0.5146, followed by 0.5415 for DMA 4 (small DMA) and 0.6268 for DMA 12 (small DMA). Therefore, it can be believed that these are the areas that should be intensively managed in the target small DMA regarding water pipe aging, civil complaints, water pressure, and water quality.

Therefore, DMA 15 is found to have a lower value by 0.4750 compared with 0.9896 (the maximum CC) among the DMAs that have been performing adequately in terms of operating and managing failure hazards, civil complaints, water pressure, and water quality. When calculating the CC value of DMA 9, the weighted normalization matrix value of the hazard assessment item used was calculated to be large, which showed the highest hazard ranking due to the increased weight ratio of water quality, leakage complaint, and failure hazard assessment items.

Figure 6 is the result of visualizing the hazard ranking based on the CC values presented in Table 2. Notably, DMAs 9 and 4 (small DMAs) had the highest failure hazard, water quality, and leak complaints. Moreover, DMA 12 (small DMA) is the second smallest DMA for failure hazards and leak complaints. Thus, the aforementioned areas had a hazard ranking as first, second, and third, respectively.

Consequently, this study suggested a methodology to identify DMAs requiring priority management by deriving risk management priorities to support maintenance decision-making in terms of the stability and service aspects of the waterworks network by comprehensively utilizing both structured and unstructured data. It is proposed that this approach will enable more effective maintenance and management of the waterworks network by establishing an improvement plan via identifying water pipelines with a high risk of failure based on the probability of failure of individual water pipelines previously calculated for effective maintenance and management decision-making of DMAs requiring priority management.

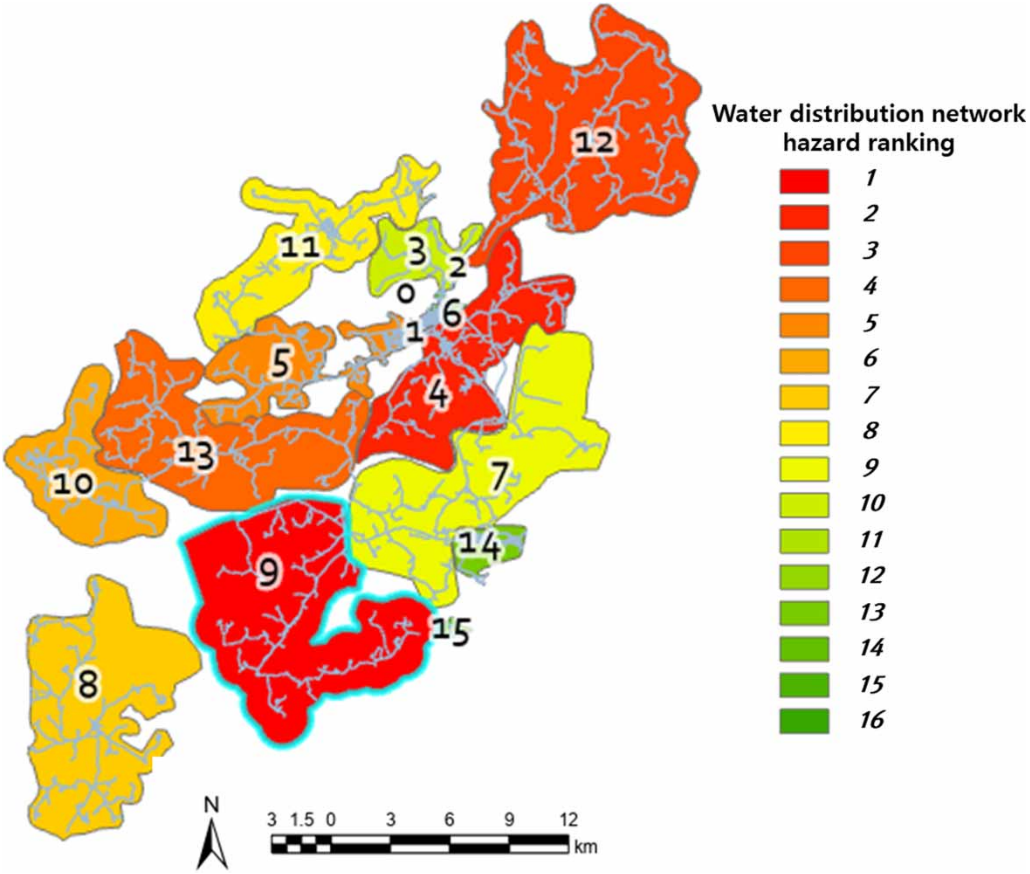


Figure 6 | Mapping the result of ranking the water distribution network hazard.

4. CONCLUSIONS

This study suggested a method to evaluate the hazard of water distribution networks and establish regional rankings from an engineering perspective by using the data that can be accumulated in the water distribution network, such as the number of failures, water quality, and leakage complaints.

The methodology comprehensively considers the designation criteria for key management areas suggested by the Water Supply and Waterworks Installation Act (the degree of aging of the water distribution network, complaints about water quality, etc.). The proposed water distribution network hazard ranking methodology supports decision-making when selecting a key management area for a water distribution network, and if it is used in establishing a network improvement and maintenance plan, the effective and sustainable maintenance of the water distribution network will be possible.

Furthermore, when developing a failure rate estimation model, it is judged that a nationally representative model can be developed if more data are secured in time and space. Additionally, it is expected that results that can be used immediately in a hands-on manner can be derived if certain information, such as the specific number of customers in each small DMA and the specific categories of complaints, can be obtained during hazard assessment.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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