Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2021.27358

227 (2021) 104–115
July

Integrated water suspension risk assessment using fault tree analysis and genetic algorithm in water supply systems

Taehyeon Kim*, Kibum Kim, Jinseok Hyung, Jayong Koo*

Department of Environmental Engineering, University of Seoul, Seoulsiripdae-ro 163, Dongdaemun-gu, Seoul 02504, Republic of Korea, Tel. +82-2-6490-2866; Fax: +82-2-6490-5465; emails: kimth0712@naver.com (T. Kim), jykoo@uos.ac.kr (J. Koo)

Received 4 January 2021; Accepted 1 April 2021

ABSTRACT

Water supply systems are exposed to various risks as they operate in an open environment. For example, climate change is increasing the frequency and intensity of droughts and water shortages. Furthermore, suspensions in water supply resulting from pipe failures and aging infrastructure result in significant economic losses to consumers and supply operators. Thus, water supply systems require integrated risk management owing to the complex interactions between subsystems; however, in most existing risk assessment studies, only single risks or individual systems are considered. Here, we analyze various causes of water supply suspensions and propose an evaluation methodology based on fault tree analysis. We also develop a genetic algorithm-based model that allows waterworks operators to optimize management plans aimed at reducing water suspension risks while simultaneously considering impact and cost.

Keywords: Water supply system; Water suspension risk; Pipe failure; Fault tree analysis; Genetic algorithm; Uncertainty

1. Introduction

Water supply systems have been developed to support economic growth and ensure the safe and reliable supply of drinking water, which is essential for human life and social development. However, water supply systems are often exposed to a range of threats and risks because they are largely designed, constructed, operated, and managed in an open environment [1]. Recently, water shortages have increasingly occurred due to droughts resulting from climate change, and many water supply suspensions due to pipe failures aging water supply infrastructure have resulted in significant economic losses. In the case of South Korea, there were cases where long-term limited water supply was inevitable because of frequent droughts. Moreover, the scale of damage from water suspension caused by pipe failure accident is showing an increasing trend, while the frequency of such accidents is also increasing. Recently, to solve this problem, a national project is also underway to renewal the old pipes.

Because these risks are uncertain, addressing them remains challenging. To tackle this, risk assessments are increasingly employed to identify and analyze water supply risks to inform appropriate risk-reduction measures, many of which have been discussed in the literature (Table 1).

Here, we analyze a range of factors causing water supply suspensions and propose an integrated methodology for evaluating their causes using fault tree analysis based on Rausand and Hojland [12]. Furthermore, we develop a novel management planning model for water supply systems using a genetic algorithm that can inform optimal

* Corresponding authors.

management plans for reducing suspension risks based on service equity, cost, and impact.

2. Material and methods

The optimal management planning model for water supply suspension risks using fault tree analysis and a genetic algorithm was developed using the framework shown in Fig. 1. The structure of the water supply system (from raw water to service reservoirs) in the study area and its components were identified alongside the potential causes of suspension. Water suspension due to water shortages resulting from drought was considered based on Kim et al. [6]. Furthermore, a water pipe failure model was developed to consider suspension resulting from the failure of aging supply infrastructure. The results of the drought and water pipe failure models were used in fault tree analysis, and the associated water suspension risks were quantitatively evaluated according to the logic gate of the fault tree. Finally, an optimal management planning model for water suspension risk was developed based on a genetic algorithm that can simultaneously consider costs and impacts for newly constructed water purification plants, double piping systems, and service reservoir capacity expansion activities. In addition, the optimal water supply suspension risk that can satisfy the target service levels of waterworks operators was established.

2.1. Study area

The maximum daily water supply of the study area is 46,422 m^3/d and the water supply area is divided into 11 reservoirs (Fig. 2 and Table 2). The water pipe from B dam to T city is composed of multi-regional and local water pipes

Table 1
Prior literatures on risk assessment of water supply system

Sub-system	Characteristics	References
Water dam	Reliability, resilience and vulnerability assessment for drought using reservoir continuity equation	[2]
	Drought risk assessment using drought frequency analysis and clusters	[3]
	Assessment of resilience against drought using system dynamics modeling of dam	[4]
	Assessment of drought metrics using general circulation model and Monte Carlo simulation	[5]
	Drought vulnerability assessment using local water resource diversification model	[6]
Water pipes	Reliability analysis of water pipes due to external stresses	[7]
	Application to sensitivity analysis of earthquake reliability model	[8]
	Risk assessment for water supply system using fault tree analysis and event tree analysis	[9]
	Risk assessment of the water supply network through segment algorithm	[10]
	Risk assessment based on the score assessment method through the vulnerability, the impact of damage, and the redundancy of the water supply network	[11]

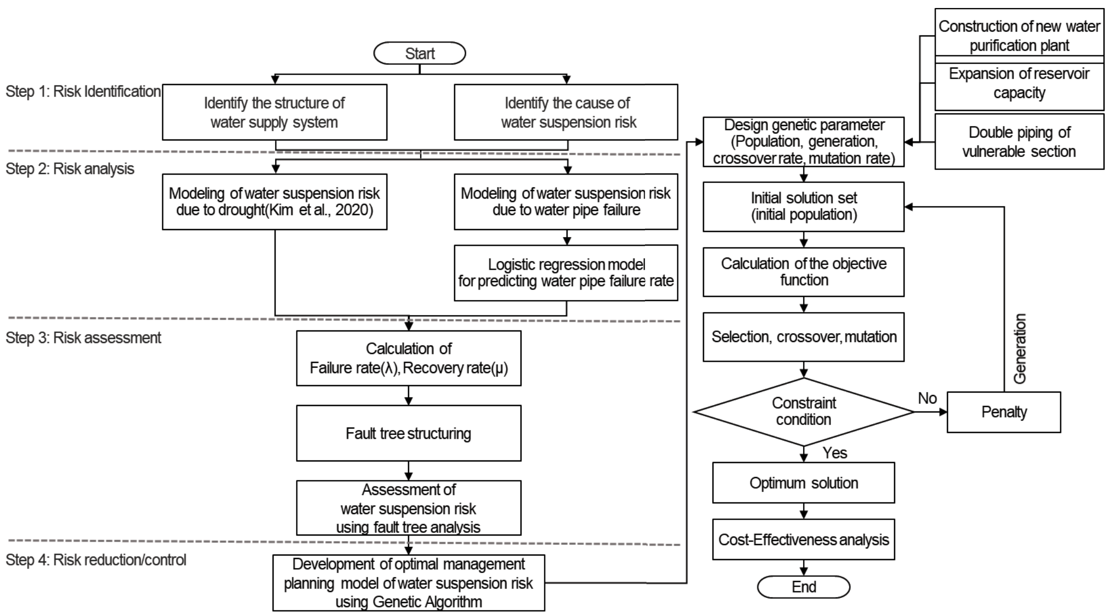

Fig. 1. Flowchart of the optimal management planning model for water supply suspension risks using fault tree analysis and a genetic algorithm.

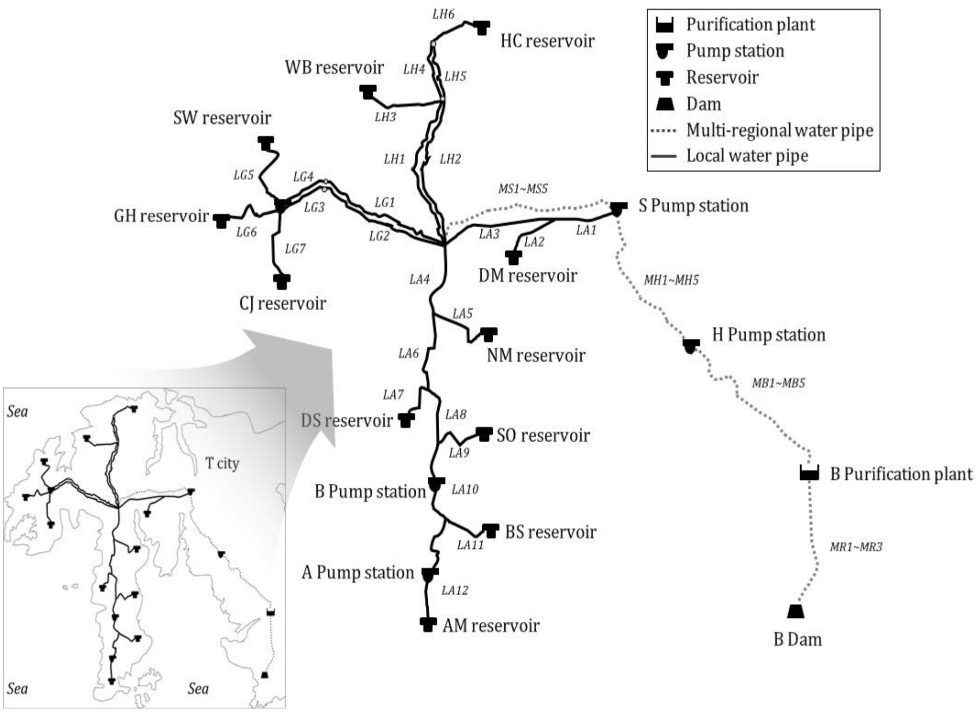

Fig. 2. Study area.

Table 2
Reservoir characteristic of study area

Category		Capacity (m^3)	Maximum daily water demand (m^3/d)
Reservoir	NM	4,700	4,700
	AM	5,000	8,518
	BS	1,750	2,589
	SO	430	841
	DS	4,000	6,438
	CJ	2,000	2,418
	GH	1,000	974
	SW	3,000	5,507
	WB	500	869
	HC	2,000	2,992
	DM	8,000	11,460

in either single or double lines. The length of the multi-regional water pipe is 102.7 km and the length of the local water pipe is 171.9 km. A total of 43 water pipe sections were established by dividing the multi-regional water pipe into 18 sections and the local water pipe into 25 sections according to the pipeline specifications and burial conditions. Table 2 lists the service reservoir capacity and the design maximum daily water supply of each water supply area in T city.

2.2. Water suspension risk

Suspension of a water supply system means that water supply to consumers is stopped for a certain period of time. Such suspensions can occur due to the new installations, expansion activities, replacement and improvement work to water pipes, the connection of existing pipelines, and sudden accidents or natural disasters. In this context, Goulter [13] employed the concept of 'water suspension risk' to numerically and quantitatively index and analyze these risks. Water suspension risk refers to a probabilistic value of the impossibility of supplying water from a supplier to consumers due to various uncertainties in the supply process, and is an index that numerically indicates the impact and margin resulting from supply failures. Here, the difference between risk and uncertainty is that uncertainties can include positive as well as negative factors while risks include losses and damage that can occur due to these uncertainties.

Choi et al. [14] defined the water supply risk of a pipe as a probabilistic water shortage that can occur when the pipe is damaged. Lindhe et al. [15] defined the risk of water supply systems as the duration of supply failures and the number of affected consumers. Common between these approaches is the expression of an expected value following the occurrence of an event based on the probability of a certain event occurring and its associated consequence.

We defined the water suspension risk as a temporal and quantitative concept. Temporally, water suspension risk was represented as the product of the suspension probability and duration in the water supply area, that is, "the total water suspension time that can occur probabilistically for 1 y in a water supply area (h/y)." Quantitatively, water suspension risk was defined as "the total amount of water suspension that can occur probabilistically for 1 y in a water supply area (m^3/y)." Both measures were calculated using Eqs. (1)–(4).

$$\text{Risk}_{T,i} = \text{PoF}_i \times \text{CoF}_i \tag{1}$$

$$\text{Risk}_{Q,i} = \text{Risk}_{Q,i} \times \text{MWD}_i \tag{2}$$

$$\text{PoF}_i = \frac{1}{\frac{1}{\lambda_i} + \frac{1}{\mu_i}} = \frac{\lambda_i \mu_i}{\lambda_i + \mu_i} \tag{3}$$

$$\text{CoF}_i = \begin{cases} \frac{1}{\mu_i} - \sum_{j=1}^{k} \frac{1}{\beta_j}, & \text{if } \frac{1}{\mu_i} > \sum_{j=1}^{k} \frac{1}{\beta_j} \\ 0, & \text{if } \frac{1}{\mu_i} \le \sum_{j=1}^{k} \frac{1}{\beta_j} \end{cases} \tag{4}$$

where $\text{Risk}_{T,i}$ is the risk of *i* reservoir area (h/y), $\text{Risk}_{Q,i}$ is the risk of *i* reservoir area (m^3/y), MWD_i is the design maximum daily water demand in *i* reservoir area (m^3/d), PoF_i is the probability of failure of *i* reservoir area (N/y), CoF_i is the consequence of the failure of *i* reservoir area (y/N), λ_i is the failure rate of *i* reservoir area (N/y), μ_i is the recovery rate of *i* reservoir area (N/y) and $1/\beta_j$ is the *j*th emergency response capability (y/N).

2.3. Fault tree analysis

The water supply system risk assessment employed fault tree analysis. Fault tree analysis is a representative modeling method for identifying the cause of failure and evaluating risks by analyzing the risks and reliability of a system and its components [16]. The most widely used logic gates of fault tree analysis are the 'OR' and 'AND' gates.

2.3.1. OR gate equation

The OR gate in Fig. 3 activates the system only when all components of the system work normally. The system operation stops if any one component has a problem, as expressed in Eqs. (5)–(8).

$$P_F = \prod_{i=1}^{n} \left(1 - P_{F,i}\right) \tag{5}$$

$$\lambda = \sum_{i=1}^{n} \lambda_i \tag{6}$$

$$\mu = \sum_{i=1}^{n} \lambda_i \frac{\prod_{i=1}^{n} \mu_i}{\prod_{i=1}^{n} \left(\lambda_i + \mu_i\right) - \prod_{i=1}^{n} \mu_i} \tag{7}$$

$$P_F = \frac{\lambda}{\lambda + \mu} = 1 - \prod_{i=1}^{n} \frac{\mu_i}{\lambda_i + \mu_i} \tag{8}$$

where P_F is the probability of failure of the top event, $P_{F,i}$ is the probability of failure of *i* basic event, λ is the failure rate of top event, λ_i is the failure rate of *i* basic event, μ is the recovery rate of top event and μ_i is the recovery rate of *i* basic event.

2.3.2. AND gate equation

The AND gate in Fig. 4 activates the system when at least one component of the system is activated. In other words, the system is stopped only when all components of the system have a problem, as expressed in Eqs. (9)–(12).

$$P_F = \prod_{i=1}^{n} P_{F,i} \tag{9}$$

$$\lambda = \sum_{i=1}^{n} \mu_i \frac{\prod_{i=1}^{n} \lambda_i}{\prod_{i=1}^{n} \left(\lambda_i + \mu_i\right) - \prod_{i=1}^{n} \lambda_i} \tag{10}$$

$$\mu = \sum_{i=1}^{n} \mu_i \tag{11}$$

$$P_F = \frac{\lambda}{\lambda + \mu} = \prod_{i=1}^{n} \frac{\mu_i}{\lambda_i + \mu_i} \tag{12}$$

where P_F is the probability of failure of the top event, $P_{F,i}$ is the probability of failure of *i* basic event, λ is the failure rate of top event, λ_i is the failure rate of *i* basic event, μ is the recovery rate of top event and μ_i is the recovery rate of *i* basic event.

Here, the water supply suspension risk was calculated using the logic gate of the fault tree proposed by Rausand and Hojland [12]. The failure rate (λ) and recovery rate

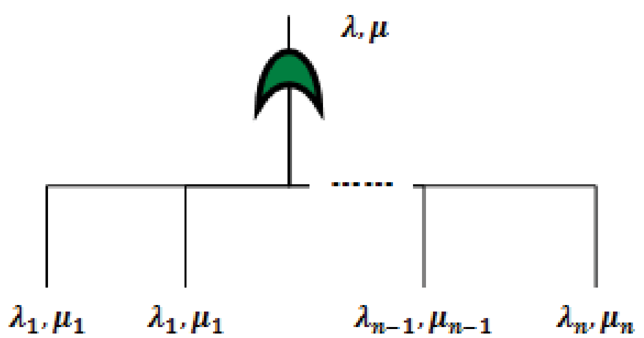

Fig. 3. Fault tree of OR gate.

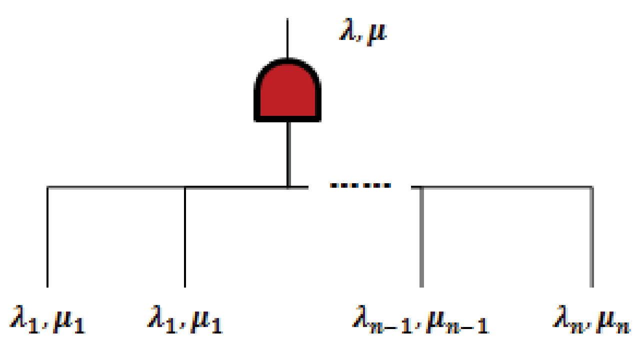

Fig. 4. Fault tree of AND gate.

(μ) of a basic event that can occur in each subsystem were calculated. The results of Kim et al. [6] for the failure and recovery rates linked to drought events were used, and the probability of pipe failure was calculated by developing a logistic regression model.

2.4. Logistic regression model for predicting water pipe failure rate

A logistic regression model was developed to predict the failure rate for each water pipe section in the study area. Previous studies have identified a range of factors influencing the performance of aging water pipes, as shown in Table 3, from which we developed the logistic regression model as variables that influence the probability of failure in each pipe section using forward stepwise selection. The suitability and significance of the model were validated using the Hosmer–Lemeshow goodness-of-fit and Wald statistical significance test.

The logistic regression model determines the relative probability of pipe failure. To use these calculations as a failure rate in the fault tree analysis, we converted the model outputs to a number of failures per unit period based on Choi and Koo [23].

$$\text{Prob}_{\text{pi}} = \frac{P_{\text{pi}}}{\text{Av}_p} \times \frac{L_{\text{total}}}{\text{Ln}_{\text{total}}} \times \text{Ln}_{\text{pi}} \quad (13)$$

$$\text{Av}_p = \frac{\sum_{i=1}^{n} P_{\text{pi}}}{n} \quad (14)$$

$$L_{\text{total}} = \sum_{i=1}^{n} L_i \quad (15)$$

$$\text{Ln}_{\text{total}} = \sum_{i=1}^{n} \text{Ln}_i \quad (16)$$

where Prob_{pi} is the failure rate of pipe i (N/y), P_{pi} is the logistic probability of failure of pipe i, Av_p is the average of logistic probability of failure of all pipes, L_{total} is the number of failure of all pipes (N/y), Ln_{total} is length of all pipes (km) and Ln_i is the length of pipe i (km).

The recovery times of pipe failure events are shown in Table 4 based on existing data on repair times according to pipe diameter in [24]. In each case, the recovery rate (μ) was calculated using the standard recovery time of a water pipe, which was used as the input data for the fault tree analysis.

Table 3
Influence factors used in pipe failure prediction model of prior studies

Reference	Influence factors
[17]	Age, length, previous failure
[18]	Age, material, previous failure, failure type, mean pressure, velocity, water age, soil type, area type
[19]	Age, diameter, length, material, location
[20]	Age, diameter, length, soil type, climate
[21]	Diameter, length, material, previous breaks, protection methods
[22]	Age, diameter, length

2.5. Optimal management planning model of water suspension risk based on genetic algorithm

Three water suspension risk management scenarios were considered. The first assumed the building of new local water purification plants through which we considered large-scale water suspension risks through concentrated water resource operation. The second scenario assumed additional emergency response capacity by increasing the storage capacity of the service reservoir. The third scenario reduced the water suspension risk by dualizing the single line pipe sections of the supply network. The objective of the optimal management planning model was to determine the scenario under which water suspension risks and the management costs of waterworks operators are minimized as in Eq. (17).

$$\text{Objective function} = \text{Minimize}\left(C_{\text{WPP}} + C_{\text{RE}} + C_{\text{DP}}\right) \quad (17)$$

where CWPP is the water purification plant construction cost (million KRW), C_{RE} is the reservoir expansion cost (million KRW), C_{DP} is the double piping (million KRW).

2.5.1. Facility capacity when constructing a new local water purification plant

As a constraint of the model and to ensure a stable supply while preventing over or under design, a newly constructed water purification plant must be designed with an operating ratio of 75% based on the planned daily maximum water supply of the water supply area, that is, Eq. (18).

$$\text{WPP}_C = 1.33 \times \text{MWD} \quad (18)$$

where WPP_C is the capacity of water purification plant (m^3/d) and MWD is the design maximum daily water demand of supply area (m^3/d).

Table 4
Standard recovery time by pipe diameter

Diameter (mm)	Recovery time (h)	Diameter (mm)	Recovery time (h)
≤300	10	900	16
400	11	1,000	18
500	12	1,100	19
600	13	1,350~1,600	22
700	14	1,650~2,000	24
800	15	≥2,000	33

2.5.2. Facility capacity when expanding the capacity of the service reservoir

The facility capacity of the service reservoir must have a storage capacity of 12 h for the planned daily maximum water supply, as suggested in the standards for water supply facilities of the Ministry of Environment [25]. Therefore, to prevent excessive expansion of the service reservoir and to set the maximum storage capacity to 16 h, Eq. (19) was established.

$$\frac{0.5\times\text{MWD}}{\text{WSR}} \leq \text{RE}_C \leq \frac{0.67\times\text{MWD}}{\text{WSR}} \quad (19)$$

where RE_C is the capacity of the reservoir expansion (m^3), WSR is the water storage rate of reservoir (%) and MWD is the design maximum daily water demand of supply area (m^3/d).

2.5.3. Target water suspension risk level for each water supply area

The target water suspension risk level of each water supply area in the study area was set as shown in Table 5. These constraints were applied together with the first objective function to "minimization of the cost of water suspension risk management plan" to establish an optimal management plan that can achieve the target water suspension risk level at a minimal cost.

The schematic construction functional equation suggested by [26] was used for determining costs. Pipe facilities must satisfy the conditions for flow rate and water pressure, thus the diameters of newly installed pipes were determined considering the target maximum daily water supply in the water supply area.

For the genetic algorithm, population, generation, crossover rate, and mutation rate parameters were set to 200, 20,000, 0.80, and 0.20, respectively. Furthermore, the genetic calculation was terminated after the calculation for the generation was completed. For the genetic algorithm, 'EVOLVER' software was used as operated in Microsoft Excel.

3. Results and discussions

3.1. Logistic regression model

To predict the probability of water pipe failure in the study area, a logistic regression model was built using 7,877 pipe sections based on accident history data for national multi-regional water supplies. Factors that can influence water pipe failure, that is, pipe age, type, inner coating, and diameter, and road types, were considered. Each of these factors was categorized for use in the logistic regression analysis using the independent variables shown in Table 6.

Of these, only the statistically significant variables were selected through a forward stepwise selection method, with nine steps in total. A likelihood test was conducted to

Table 5
Target water suspension risk level of each water supply area

Scenario	Objective function	Target water suspension risk (h/y)
A-1		48
A-2		42
A-3	Minimize cost	36
A-4		30
A-5		24

Table 6
Independent variables in logistic regression analysis

Variable	Category	Explanation	Sample size (ratio)
Age (year)	Age 1	>30	1,151 (14.61%)
	Age 2	25–30	888 (11.27%)
	Age 3	20–25	781 (9.91%)
	Age 4	15–20	1,342 (17.05%)
	Age 5	10–15	2,022 (25.67%)
	Age 6	≤10	1,693 (21.49%)
Material	Material 1	SP	4,321 (54.86%)
	Material 2	DCIP	3,556 (45.14%)
Inner coating	Coating 1	Presence	4,314 (54.77%)
	Coating 2	Absence	3,563 (45.23%)
Diameter (mm)	Diameter 1	<500	2,001 (25.40%)
	Diameter 2	500–1,000	2,301 (29.21%)
	Diameter 3	1,000–1,500	1,740 (22.09%)
	Diameter 4	≥1,500	1,835 (23.30%)
Road type	Road 1	Road	2,350 (26.83%)
	Road 2	Land	4,727 (60.01%)
	Road 3	River or other	800 (10.16%)

identify the explanatory power of the resulting nine independent variables (Table 7). In each step, the model signifies the difference between the –2LL (Log-likelihood) value of the basic model with intercepts only and the –2LL value of the analysis model, with a larger difference indicating higher explanatory power. 'Step' is the difference in the –2LL value between two successive steps and 'block' is the difference in –2LL between two successive blocks when multiple blocks are set in the analysis. After nine steps, the model achieved a χ^2 (chi-square) value of 681.524 (degrees of freedom = 9) and was statistically significant ($p < 0.000$). To test the validity and goodness-of-fit of the logistic regression model, the Hosmer–Lemeshow goodness-of-fit test was also conducted, yielding a value of 0.308 ($p < 0.05$) (Table 8). Thus, the resulting model [Eq. (20)] predicted the pipe failure rate with high confidence.

$$P = \frac{1}{1+e^{-z}} \tag{20}$$

$$Z = -1.687 + 1.003(\text{Age 1}) + 0.285(\text{Age 3}) - 0.340(\text{Age 4})$$
$$-0.882(\text{Age 5}) - 1.346(\text{Age 6}) - 0.523(\text{Material 2})$$
$$-0.455(\text{Diameter 4}) - 0.523(\text{Material 2})$$
$$-0.455(\text{Diameter 4}) + 0.496(\text{Road 1}) + 0.494(\text{Road 3}) \tag{21}$$

where P is the failure rate of pipe (N/y).

Based on this model, 'Age 1', 'Age 3', 'Road 1', and 'Road 2' were identified as key variables contributing to failure. Specifically, older pipes have a higher probability of failure, as reflected in the model coefficients of determination. Furthermore, pipes buried in a road or river were also identified as having a high probability of failure. For example, when a pipe is buried in a road, the probability of failure increases due to higher loading stresses from the road above. Furthermore, when a pipe is buried in a river, failure can occur due to the corrosiveness of the surrounding sediment and water. In contrast, the variables 'Age 4', 'Age 5', 'Age 6', 'Material 2', and 'Diameter 4' were associated with a reduced probability of failure. This suggests that the lower the number of years elapsed after burial (under 15 y), the lower the probability of failure. In the case of pipe type, DCIP showed a lower probability of failure than SP. Thus, while DCIP has a smaller diameter, its large thickness reduces the probability of failure; larger diameter pipes have a lower probability of failure as a function of pipe strength.

Table 7
Omnibus tests of model coefficients

	χ^2	df	Sig.	–2LL
Step	6.458	1	0.011	5,302.097
Block	681.524	9	0.000	
Model	681.524	9	0.000	

Table 8
Hosmer–Lemeshow goodness-of-fit test

Step	χ^2	df.	Sig.
9	8.287	7	0.308

To apply the model values in the fault tree, the pipe failure probabilities were converted to the number of failures per unit period of time. The failure rates of the 42 water pipe sections in the study area are shown in Table 9, with a maximum of 0.433 N/y, a minimum of 0.001 N/y, and a mean value of 0.071 ± 0.088 N/y. This variability results from physical factors such as the number of years after burial, pipe type, pipe diameter, and environmental factors including ground topography. Among the regional water pipe sections, MH5 and MS3 showed high failure rates, and among the local water pipe sections, LG3 showed a high failure rate. These high failure rates primarily relate to the number of years elapsed after burial, which is higher than 25 y in these cases, and that these pipes are buried under roads. Furthermore, the relatively long length of these pipe sections is another likely cause of their high failure rates.

3.2. Water suspension risk assessment

The calculated temporal and quantitative water suspension risks for the study area are shown in Figs. 5 and 6. The average water suspension risk of the study area is 49.99 h/y (2.08 d/y) and ranged from 43.47 h/y (in the GH water supply area) to 53.37 h/y (in the SO water supply area). This variability reflects the water supply system, emergency response capability (e.g., service reservoir residence time and

Table 9
Failure rate and state of each pipe

Pipe code	Failure rate (N/y)	Pipe code	Failure rate (N/y)
MR1	0.009	LG5	0.081
MR3	0.001	LG6	0.039
MB1	0.026	LG7	0.035
MB2	0.023	LH1	0.105
MB3	0.097	LH2	0.031
MB4	0.190	LH3	0.000
MB5	0.165	LH4	0.074
MH1	0.088	LH5	0.022
MH2	0.148	LH6	0.001
MH3	0.090	LA1	0.073
MH4	0.172	LA2	0.004
MH5	0.204	LA3	0.006
MS1	0.108	LA4	0.015
MS2	0.002	LA5	0.003
MS3	0.260	LA6	0.062
MS4	0.008	LA7	0.001
MS5	0.032	LA8	0.025
LG1	0.008	LA9	0.011
LG2	0.002	LA10	0.037
LG3	0.433	LA11	0.001
LG4	0.197	LA12	0.092

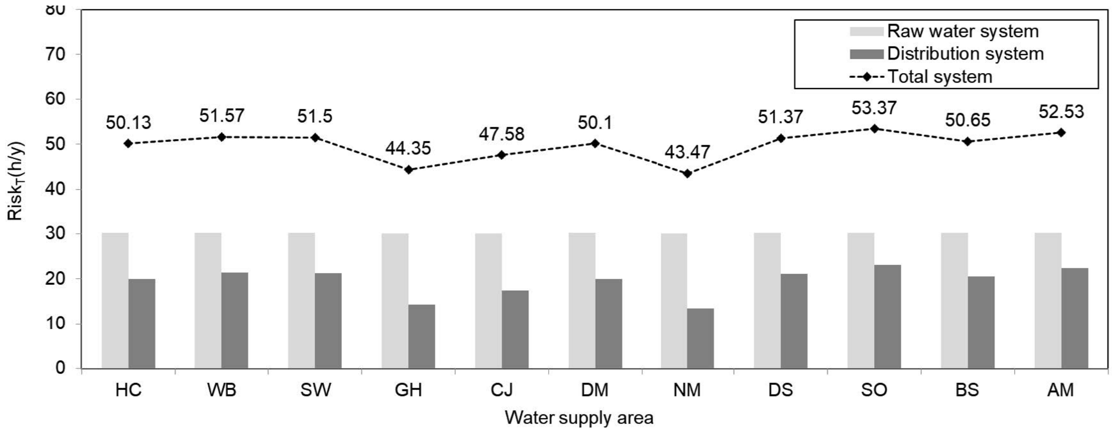

Fig. 5. Result of water suspension risk assessment (temporal, h/y).

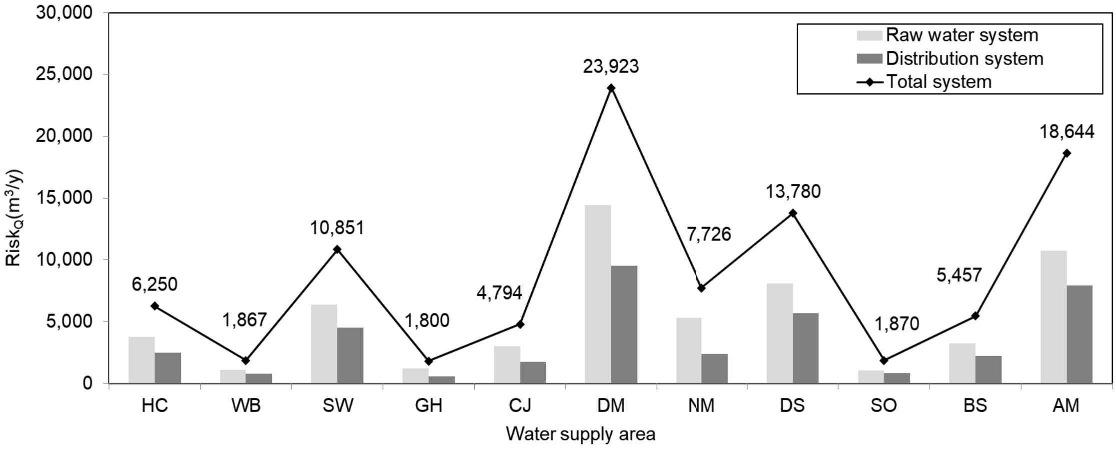

Fig. 6. Result of water suspension risk assessment (quantity, m^3/y).

water purification pond residence time), and planned daily maximum water supply (i.e., water supply population) in the different supply areas. It can be seen that when the target water suspension risk level is set below 48 h/y (i.e., 2 d/y), all the water supply areas fail to meet the requirements except for GH and NM. Therefore, an optimal water supply suspension risk management plan needs to be established to minimize costs while ensuring an equitable water supply by selecting more targeted risk levels for each supply area rather than a generally applied target.

3.3. Optimal management planning model for water suspension risk

Scenarios A-1 to A-5 were defined by setting the target water supply suspension risk level of consumers or waterworks operators, and a management plan able to meet these targets with minimal costs was established. Here, to reduce the water suspension risk, we considered the strategies of securing additional emergency response capacity, constructing a new local water treatment plant, and dualizing vulnerable water pipes.

Based on our analysis, it is impossible to reduce the temporal water suspension risk of every water supply area while also considering service equity by expanding the facility capacity of the service reservoir. Furthermore, the strategy to dualize vulnerable pipes would require more than 60 km of upgrading to large-diameter pipes at a cost of more than 100 billion the Korean Republic won (KRW). Therefore, constructing a new local water treatment plant with a capacity of 14,272 m^3/d to supply the NM and DS supply areas is favored, as shown in Table 10 and Fig. 7. Additionally, dualizing 8.585 km of water pipes and expanding the facility capacity of the service reservoirs in the HC, WB, SW, SO, BS, and AM supply areas is required. Scenario A-3 had a higher target risk level than Scenario A-2, which requires more flexible and active management plans to ensure minimal costs. By constructing a new water treatment plant, dualizing pipes, and expanding the facility capacity of the service reservoirs, the water supply suspension risk in all supply areas could be reduced to below 36 h/y, and the minimum cost required to satisfy Scenario A-3 is 54,639 million KRW. Fig. 8 shows the effects of the optimal management strategies on meeting the target risk levels for Scenarios A-1 to A-5.

3.4. Cost-effectiveness analysis

Table 11 shows the costs required to establish the optimal management plans for Scenarios A-1 to A-5 classified

Table 10
Results of Scenario A-3 (target level of water suspension risk: 36 h/y)

Water supply area	Optimal management planning			Cost and water suspension risk reduction		
	Expansion capacity of reservoir (m^3)	New local purification plant capacity (supply reservoir)	Double piping length (pipe code)	Total cost (million KRW)	Water suspension risk reduction (m^3/y)	Water suspension risk reduction (h/y)
HC	200				1,804	14.47
WB	200				611	16.87
SW	700				3,321	15.76
GH	0				525	12.94
CJ	0				1,338	13.28
DM	0	14,272 m^3/d (NM, DS)	8.585km (MB1, MB2, MH4)	54,639	6,753	14.14
NM	0				7,214	40.59
DS	0				12,984	48.40
SO	200				610	17.40
BS	190				1,585	14.70
AM	1,500				5,932	16.71

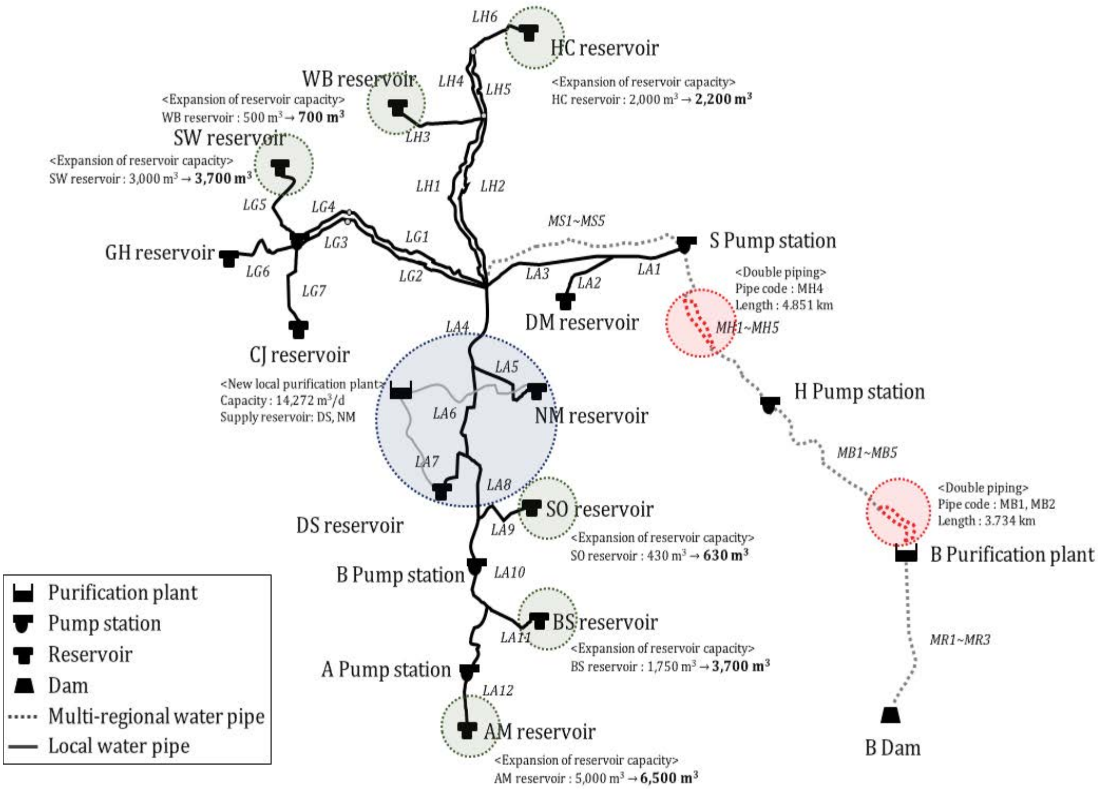

Fig. 7. Result of plan drawing in the study area (Scenario A-3).

based on the cost of expanding the facility capacity of the service reservoir, constructing a new water treatment plant, and dualizing the pipe network. The results of the five scenarios confirmed that as the target water suspension risk level increased from 48 h/y (Scenario A-1) to 24 h/y (Scenario A-5), the required costs of implementation also increased. When the target risk level of waterworks operators was similar to the current risk level, the target could be satisfied at a lower cost than dualizing vulnerable pipe sections or expanding the facility capacity of some of the service reservoirs. However, when the target risk level was very different from the current risk level, this could not be met using simple, low-cost interventions. Therefore, to achieve the target level of risk, it is necessary to construct a new local water treatment plant to directly supply some areas or dualize many

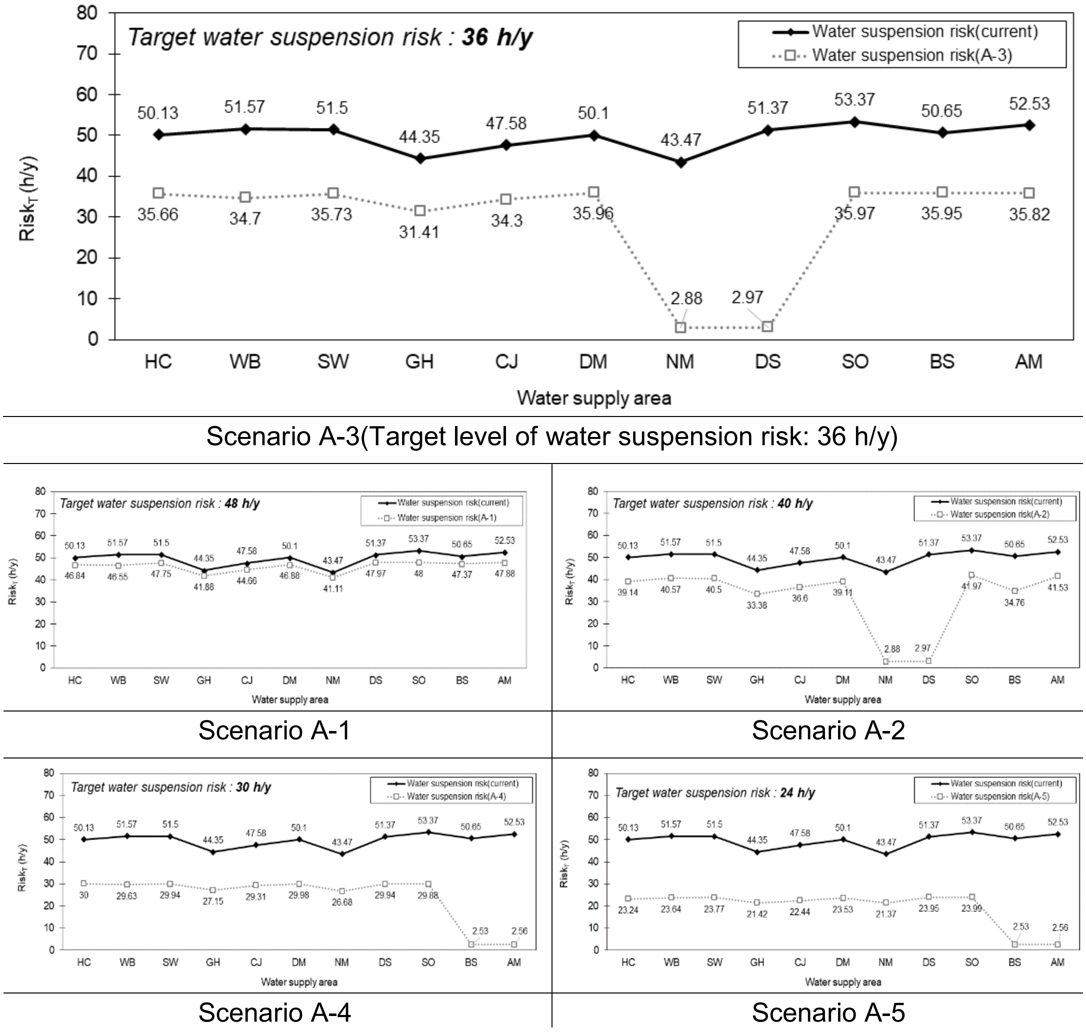

Fig. 8. Result of achieving target water suspension risk for each water supply area by scenario.

Table 11
Detailed cost and water suspension risk of Scenario A

Scenario	Cost (Billion KRW)				Effectiveness (h/y)			Cost-effective (h/y/Billion KRW)
	Reservoir expansion	New local purification plant construction	Double piping	Total cost	Target water suspension risk	Water suspension risk	Water suspension risk reduction	
A-1	1.169	0	17.543	18.712	48	46.09	3.90	0.21
A-2	0.842	37.002	0	37.844	42	32.13	17.86	0.47
A-3	3.9	37.002	13.737	54.639	36	29.21	20.78	0.38
A-4	4.342	37.352	42.211	83.905	30	24.33	25.66	0.31
A-5	0.175	37.352	90.985	128.512	24	19.31	30.68	0.24

sections of water pipes, with consequent cost increases. Moreover, if waterworks operators sought to reduce the current risk level from 48 to 42 h/y, the corresponding cost is 3,189 million KRW per 1 h/y reduction, as shown in Fig. 9. In contrast, to reduce the risk level from 36 to 30 h/y, the reduction cost more than doubles to 7.435 million KRW. In other words, an initial investment to reduce the current level of water suspension risk should prove most cost-effective, as additional costs rapidly accumulate when a greater degree of risk reduction (relative to the current risk) is required. Therefore, when establishing management plans to reduce water suspension risks, waterworks operators should set an appropriate target based on the required level of reduction and the associated costs.

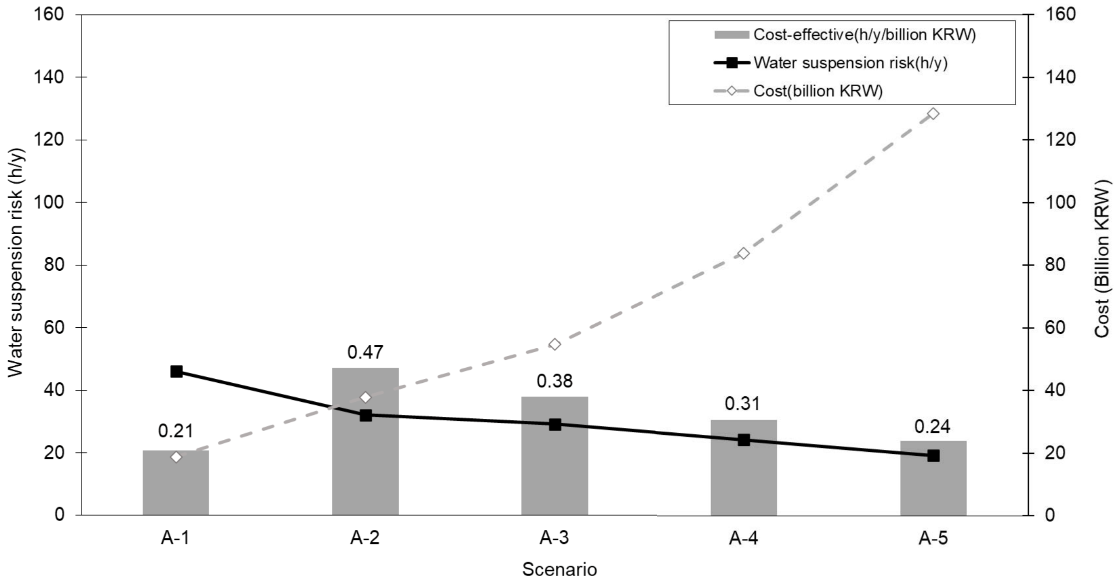

Fig. 9. Results of cost-effectiveness analysis.

For our study area, 42 h/y was the most effective target based on costs alone. However, as consumer service demand will likely continuously increase in the future, despite higher costs, waterworks operators need to set high target risk levels as part of future investment plans.

4. Conclusions

We analyzed the causes and probability of water supply suspensions in the study area using fault tree analysis. In addition, we developed a model to optimize management planning that simultaneously accounted for impacts on supply and costs for waterworks operators. Our logistic regression model for predicting pipe failure probabilities yielded an average failure rate of 0.071 N/y but with considerable variability between 0.001 and 0.433 N/y.

The water supply suspension risk in each supply area was evaluated based on the failure rate, recovery rate, and emergency response capacity using fault tree analysis. The DM water supply area was identified as being vulnerable to water suspension, with temporal and quantitative water suspension risks of 50.1 h/y and 23,923 m^3/y, respectively. Importantly, our approach offers a useful methodology for determining investment and improvement priorities for waterworks operators.

Based on our optimization model, Scenario A-2 (target water suspension risk = 42 h/y) yielded a per unit risk reduction cost of 98 m^3/y per 100 million KRW. However, whilst this target is favorable based on cost alone, higher target risk levels should be considered in future investment plans to account for expected increases in consumer demand. Nonetheless, our results can support the design of mid- to long-term plans to ensure ongoing stable water supplies.

Acknowledgments

This subject is supported by the Korean Ministry of Environment as Global Top Project (2016002120006).

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