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A water supply risk assessment model for water distribution network

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ABSTRACT

A water supply risk (WSR) assessment model was developed for a water distribution network and applied in a targeted area for determining the pipe burst probability ($Prob_{PB}$), the impact of pipe burst (Imp_{PB}), and the WSR calculated as the product of these two values. Imp_{PB} was separately calculated for the leakage duration time and the repair work time when water service is cut-off or reduced. The WSR for the block in the study area was calculated at 1.507 m^3/year. To verify this WSR, pipe replacement was performed based on $Prob_{PB}$, which is a management indicator for the water provider, Imp_{PB}, which is a management indicator for the water consumer, and the WSR that considers both of these, by analyzing the WSR reduction effect of each. The pipe replacement cost, which is a restrictive condition, was set at 5% of the full replacement cost (5.3 billion won) for the entire pipe network in the targeted area. Pipe replacement was performed based on $Prob_{PB}$, Imp_{PB} and WSR. The block WSR reduction efficiency for pipe replacement was calculated at 0.524 m^3/year/billion won based solely on $Prob_{PB}$, 2.163 m^3/year/billion won based solely on Imp_{PB}, and 2.173 m^3/year/billion won based on concurrent consideration of both factors by introducing the concept of WSR. Hence, the reduction efficiency was the highest for pipe replacement based on WSR. The study results demonstrated the capability of the proposed WSR assessment model to concurrently consider the positions of both water provider and water consumer. In addition, the cost effectiveness of the model was verified.

Keywords: Water supply risk; Pipe burst probability; Impact of pipe burst; Logistic regression analysis; ISM

1. Introduction

With economic and cultural development, consumers require better water supply service. However, water-pipe network management has traditionally focused only on enhancing the revenue water ratio. Thus, effort of objective assessment for water supply service satisfaction lack tangibly.

Along with eventual goals of securing water resources, healthy management, and stable water supply, continual efforts on leakage reduction have enabled the upsurge of revenue water ratio (83.5%) as of late 2011 in the Republic of Korea. Nonetheless, the number of civil complaints increased drastically from

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Table 1
Studies of WSR in water pipe networks

Topological risk (TR)		Hydraulic risk (HR)	
Name (year) Ref.	Method	Name (year) Ref.	Method
Tung (1985) [1]	Cut set method	Cullinane (1986) [14]	Staireway function
Goulter (1986) [2]	Junction isolation probability	Su (1987) [15]	Minimum cut set method
Wagner (1988) [3,4]	Junction connectivity analysis	Bao (1990) [16]	Monte carlo simulation
Goulter (1990) [5]	$Prob_{PB}$	Fujiwara (1993) [17]	Minimum cut set method
Shamsi (1990) [6]	Node pair reliability	Yang (1996) [18]	Stochastic simulation
Kansal (1995) [7]	ASP algorithm	Khomsi (1996) [19]	Water network analysis
Yang (1996) [8]	Minimum cut set method	Gargano (2000) [20]	Stochastic simulation
Isoyama (2000) [9]	$Prob_{PB}$	Park (2003) [21]	Minimum cut set
Chen (2002) [10]	$Prob_{PB}$	Al-Zahrani (2004) [22]	Hydraulic simulation
Jun (2005) [11]	Segment and UI	Paik (2007) [23]	HSPDA
Wang (2009) [12]	Critical link	Kim (2009) [24]	HDSM
Lee (2011) [13]	Safety, restoration, and impact index	Yoo (2012) [25]	Quasi-PDA

549,432 in 2007, when statistics regarding water supply-related complaints began to be collected, to 1,397,942 in 2011. As this result implies that people need improved water supply service, a variety of service items such as water quantity, water quality and water pressure should be upgraded.

The number of water cut-offs has remained almost constant around 27,000 since 2007. This level of water cut-offs indicates that the pipe networks constructed during rapid-growth periods need to be replaced via strategic approaches.

Even though the provision of water supply is well managed, these efforts are unappreciated when the effects of water supply service are not felt by consumers. Therefore, to enhance water supply service satisfaction, consumers' interests should be considered in water supply management. As the revenue water ratio is a key water supply management indicator for providers, water supply management indicators from the consumers' perspective should be prepared. Thus, this study proposes the concept of water supply risk (WSR) to help develop assessment indicators and models capable of considering consumers' interests rather than provider-oriented management.

Numerous studies related with WSR assessment were reviewed in order to determine the essential items for developing the WSR assessment model. These items were classified into two types: topological risk (TR), which is related with the probability of physical disconnection of components in a specific water pipe network, and hydraulic risk (HR), which is the probability that water cannot be supplied to consumers with suitable node quantity and pressure.

For the study purpose, research trends were examined. Table 1 shows the trends arranged according to TR and HR.

In order to develop a WSR assessment model of a water distribution network, a study method including both TR and HR is proposed. To this end, pipe burst probability ($Prob_{PB}$) estimation, hydraulic pipe network analysis based on pipe burst, and TR estimation based on gate valves are utilized.

2. Methods

The WSR assessment model of water distribution network is expressed as the product of $Prob_{PB}$ and the impact of pipe burst (Imp_{PB}). Imp_{PB} was classified into an impact index of leakage duration time (LDT, from pipe burst to gate valve closure) and a impact index of repair work time (RWT, from gate valve closure to repair completion). The sum of these two indexes was treated as the total impact index of the pipe burst. The assessment model was developed to estimate the impacts of water supply cut-off and water supply cut-down based on the positions of valve installation and the positions of pipes, and emergency connective pipes.

$Prob_{PB}$ was calculated using logistic regression analysis, and the impact of LDT was calculated using EPANET 2.0 emitter. On the assumption that the leakage quantity is proportional to the pressure of the node that each pipe reaches, after leakage production, the demand shortage at all nodes was calculated in order to estimate the impacts. The impact on RWT was calculated using Interpretive Structural Modeling (ISM) and a concept of "segment" based on gate valve boundary. To repair a pipe burst, a gate valve in the closest distance is closed, and "segments" are then made. Imp_{PB} on RWT was estimated by calculating the total demand shortage of "segments" caused by gate valves that were closed for pipe repair.

LDT and RWT for each pipe were estimated by multiple regression analysis, and were then multiplied by the impacts of LDT and RWT in order to quantify the volume.

Therefore, the WSR for each pipe is expressed as the product of $\mathrm{Prob_{PB}}$ and $\mathrm{Imp_{PB}}$, which is the demand shortage arising from $\mathrm{Prob_{PB}}$. Furthermore, in order to estimate the WSR for each block, the WSR values of pipes in the same block were averaged and this average was defined as WSR for each block. The research procedure is presented in Fig. 1.

2.1. Target area

In this study, to estimate $\mathrm{Prob_{PB}}$, LDT, and RWT of pipe burst, the GIS of total pipes in S city, leakage repair registers and water-demand data were used. Block A2 in K water supply region was set as the study area to assess the WSR of pipes and of blocks. The A2 Block has 84 pipes, 237 hydrants, and a pipe length of 5,706 m. The total demand of this region is 813.34 $\mathrm{m^3/day}$.

2.2. Assessment model development of $Prob_{PB}$

A $\mathrm{Prob_{PB}}$ function was produced by applying logistic regression. Logistic regression can be used to obtain the $\mathrm{Prob_{PB}}$ of each pipe unit, whereas previous statistical approaches predicted bursts in pipe groups that have similar characteristics. Therefore, it was deemed an appropriate approach. A commercialized statistics package, SPSS version 18, was used in the logistic regression. Table 2 explains the variables used.

The $\mathrm{Prob_{PB}}$ estimated through logistic regression is the relative $\mathrm{Prob_{PB}}$ for each pipe. To apply it in the WSR assessment model, the number of bursts per unit length and unit period was determined by using Eq. (1).

$$Prob_{pi} = \frac{P_{pi}}{Av_p} \times \frac{L_{total}}{Ln_{total}} \times Ln_{pi}$$

$$Av_p = \frac{\sum_{j=1}^{n} P_{pj}}{n}$$

$$L_{total} = \sum_{j=1}^{n} L_j$$

$$Ln_{total} = \sum_{j=1}^{n} Ln_j \qquad (1)$$

where $Prob_{pi}$: $\mathrm{Prob_{PB}}$ of pipe i (no./year); P_{pi}: $\mathrm{Prob_{PB}}$ of pipe i for logistic regression analysis; Av_p: $\mathrm{Prob_{PB}}$ average of all pipes for logistic regression analysis; L_{total}: total leakage number of all pipes (no./year); Ln_{total}: total pipe length of all pipes (m); and Ln_{pi}: pipe length of pipe i (m).

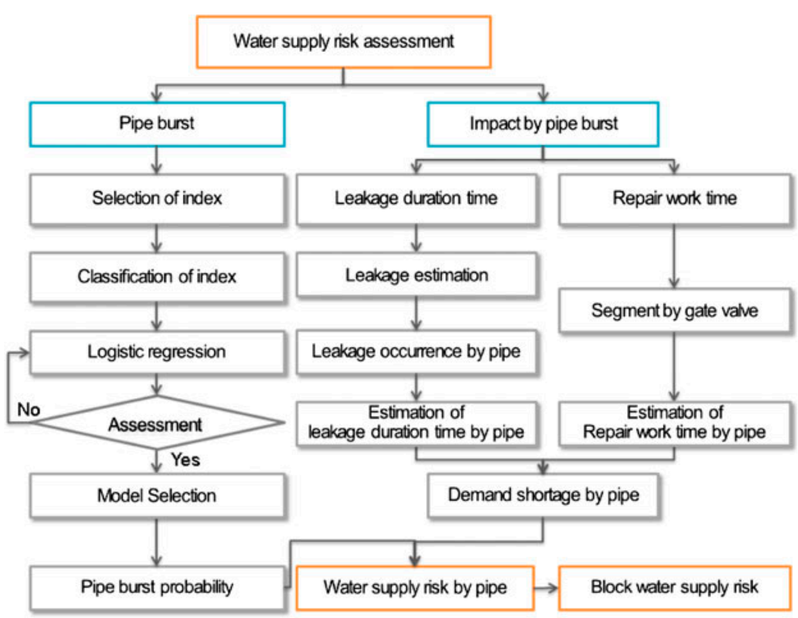

Fig. 1. Flow chart for developing the WSR assessment model.

Table 2
Variables used in the logistic regression analysis

Variable	Type	Explanation
Prob.	Binary	Dependent variable: 1, if pipe failure occurred; 0, otherwise
Diameter	Category	Independent variable: 1. diameter < 80 mm, 2. 80 ≤ diameter < 100 mm, 3. 100 ≤ diameter < 200 mm, 4. 200 ≤ diameter < 300 mm, 5. 300 ≤ diameter < 400 mm, 6. 400 ≤ diameter < 600 mm, and 7. diameter ≥ 600 mm
Material	Category	Independent variable: 1. STS, 2. DCIP, 3. SP, 4. PVC, 5. PE, and 6. CIP
Age	Category	Independent variable: 1. ≤5 year, 2.6~10 year, 3.11–15 year, 4.16–20 year, 5.21–25 year, 6.26–30 year, and 7. ≥31 year
Depth	Category	Independent variable: 1. <1.0 m, 2. 1.0–1.5 m, and 3. >1.5 m
Road	Category	Independent variable: 1. footway, 2. unpaved 3. 2 lane road, and 4. ≥4 lane road
Area		characteristic
Category		Independent variable: 1. not busy, 2. residential, and 3. mixed (residential + commercial)

STS: stainless steep pipe, DCIP: ductile cast iron pipe, SP: coated and wrapped steel pipe, PVC: polyvinyl chloride pipe, PE: polyethylene pipe, and CIP: cast iron pipe.

2.3. Estimation of the impact by pipe burst

Imp_{PB} is classified into the impact on LDT and that on RWT. To calculate the impact on LDT, after estimating the amount of leakage caused by pipe bursts randomly occurring in the node that the pipe reaches, using EPANET 2.0 emitter, the demand shortage of total nodes was calculated and assessed. To calculate the impact of RWT using segmentalization by gate valve closure, the demand shortage was estimated using ISM. The LDT and RWT of each pipe were estimated by multiple regression analysis. Imp_{PB} was quantified as the unit volume of water by applying the estimated values.

2.3.1. Leakage estimation

LDT is the duration of leakage caused by pipe burst. Since leakage reduces nearby node pressures, demand shortage can occur at the node. Pipe network analysis through pressure-driven demand analysis is used to analyze the demand shortage. In this analysis, using EPANET 2.0 emitter, the production of leakage quantity in each pipe is simulated to calculate the nearby node demand.

Water pressure affects leakage quantity directly. Due to the numerous factors affecting leakage quantity, such as leakage site shapes, and burial environment, data collection is difficult at leakage sites, and accurate leakage quantity cannot be easily measured. Therefore, the orifice equation shown in Eq. (2) was applied to estimate Imp_{PB} on LDT from pipe burst and to analyze the changes in Imp_{PB} on LDT from pipe burst. Furthermore, the changes in Imp_{PB} on LDT from pipe burst were analyzed based on the exponentiation of water pressure.

$$q_L = CA\sqrt{2gH} = 0.64 \times a\sqrt{2 \times 9.8 \times 10P} \times \frac{3,600}{10,000} = 3.2aP^{1/2} = 3.2a\sqrt{P} \quad (2)$$

where a: area of leakage hole (cm^2); A: area of leakage hole (m^2); C: coefficient of discharge = 0.64; g: acceleration of gravity ($9.8 m/s^2$); H: head (m) = 10P; and P: water pressure (Kg_f/cm^2).

2.3.2. Estimation of LDT and RWT

LDT and RWT in each pipe need to be estimated to measure the demand shortage induced by pipe burst on unit volume, not unit time.

LDT is the duration time that elapses from the dispatch of repair personnel to the completion of gate valve closure after receipt of a pipe burst report. LDT is not affected by burial characteristics such as pipe material, pipe diameter, pipe age, depth, and roads, but by how pipe burst reports are generated and the speed of repair personnel dispatch. Thus, the use of a fixed value of LDT per pipe can be more practical. In this study, a fixed value was used for WSR assessment. RWT can be affected by factors such as pipe material, pipe diameter, pipe age, depth, and roads. Thus, for the RWT assessment, the influencing factors such as pipe material, pipe diameter, pipe age, depth, and roads were applied. The LDT and RWT of each pipe were estimated using multiple regression analysis.

A commercialized statistics package, SPSS version 18, was used in the multiple regression. Table 3 explains the variables used.

2.3.3. Estimation of the Impact by Pipe Burst on LDT

$\mathrm{Imp}_{\mathrm{PB}}$ on LDT was estimated by calculating the demand shortage at total nodes after producing simulated leakage at the node that the pipe reaches on the pipe network map. To estimate the simulated leakage produced at this node, the orifice equation in proportion to water pressure was used, and the impact of simulated leakage on the nearby nodes was estimated using EPANET 2.0 emitter.

The actual demand and pressure at each node were calculated in order to analyze the existing pipe network map by using EPANET 2.0 emitter, after executing the EPANET 2.0 input file in which demand at each node was input as a base demand. Then, after setting the existing node base demand as 0, the emitter coefficient on the node that was calculated using Eq. (3) was input.

$$q_d = C_d H^r \tag{3}$$

where q_d: base demand of node (m^3/day); H: node pressure prior to the pipe burst (m); r: leakage exponent; and C_d: emitter coefficient prior to the pipe burst.

In the case of pipe burst leakage, the demand shortage at all nodes is estimated by adding the emitter coefficient converted from the leakage amount to the emitter coefficient at the node prior to the pipe burst, and by executing EPANET 2.0 emitter, as show in Eq. (4).

$$q_L = C_L H^r$$

$$C_L = \frac{q_L}{H^r}$$

$$q = q_d + q_L$$

$$C = C_d + C_L \tag{4}$$

where q_L: estimated leakage in the pipe burst (m^3/day); and C_L: emitter coefficient for estimated leakage in the pipe burst.

Therefore, the leakage quantity in the pipe is simulated to calculate the variation in the node demand, and the demand shortage of LDT is then calculated, as shown in Eq. (5).

$$impact_{pi}^{1st} = \sum_{j=1, j\in i}^{n} before\_demand_j^i - \left(\sum_{j=1, j\notin i}^{n} after\_demand_j^i + C_d H_a^r \right) \tag{5}$$

where $impact_{pi}^{1st}$: demand shortage of LDT for burst of pipe i (m^3/day); $before\_demand_j^i$: actual demand of node j, prior to the burst of pipe i (m^3/day); $after\_demand_j^i$: actual demand of node j, since the burst of pipe i (m^3/day); and H_a: pressure of reaching node since the burst of pipe i (m).

The demand shortage of LDT of each pipe is similarly calculated for all pipes.

2.3.4. Estimation of impact by pipe burst on RWT

Regarding $\mathrm{Imp}_{\mathrm{PB}}$ on RWT, the locations of gate valves were represented on the pipe network map, the area isolated by gate valves was defined as a "segment", and the assignment segment demand in the segment was estimated using ISM. The details are presented as follows.

2.3.4.1. Representation of gate valves on the pipe network map. Gate valves on the pipe network map were represented by a node-pipe matrix. Each of all the pipes is connected by two nodes. According to which node direction of the pipe the gate valve is placed in, the numeral letter "1" is marked at the location of the node number and the pipe number, and in this manner, the gate valves are represented on the pipe network map.

Table 3
Variables in multiple regression analysis

Variable	Explanation
Time	Dependent variable: repair time of failure pipe (h)
Material	Independent variable: PVC, CIP, DCIP
Diameter	Independent variable: 80~150 mm, 200–350 mm, over 400 mm
Age	Independent variable: 0–10 year, 11–20 year, 21–30 year, over 31 year
Depth	Independent variable: 0–1.2 m, over 1.2 m
Road	Independent variable: footway, 2 lane road, ≥ 4 lane road

2.3.4.2. Segmentalization process by gate valve closure. When a specific pipe is burst, all the gate valves around it should be closed to prevent leakage. As a result, the area isolated by the closed gate valves that is created can be defined as a "segment". When gate valves are closed because of pipe burst, the demand of all the segments is defined as the assignment segment demand. In other words, the demand shortage of a segment made due to gate valve closure equals the assignment demand in the same segment. Furthermore, the impact of RWT in all the pipes of the segment produced by gate valve closure equals the assignment demand in the same segment.

Similarly, to estimate Imp_{PB} on RWT by the "segment", the "segmentalization process" is conducted using the locations of gate valves in the pipe network. The "segmentalization process" was applied using the segment algorithm suggested by Jun [11].

2.3.4.3. The conversion of the node demand into the pipe demand. Even in a real pipe network, since a number of supply pipes are connected to a single water distribution pipe, the distribution of the water demand through the distribution pipe can be more practical. On the pipe network map, the conversion of the node demand into the pipe demand is made using Eq. (6).

$$P_d = \left(SN_d \times \frac{L_p}{\sum_{i=1}^{n} SNL_i}\right) + \left(EN_d \times \frac{L_p}{\sum_{i=1}^{n} ENL_i}\right) \quad (6)$$

where P_d: water demand of pipe (m^3/day); SN_d: water demand of 1st node on the pipe (m^3/day); EN_d: water demand of 2nd node on the pipe (m^3/day); L_p: length of target pipe (m); SNL_i: length of pipe i linked 1st node on the pipe (m); and ENL_i: length of pipe i linked 2nd node on the pipe (m).

As above, the water demand at all the nodes is converted into the pipe demand for the estimation of Imp_{PB} on RWT.

2.3.4.4. Estimation of the impact by pipe burst on RWT. Regarding Imp_{PB} on RWT, Imp_{PB} in a specific segment was estimated by measuring the impact of a segment on another segment, and the product of Imp_{PB} and RWT was used for the quantification.

ISM, a graphic theory, was applied to solve the relations mathematically. ISM was used by Nishizawa (2012). When gate valves were closed due to pipe burst, the water cut-off quantity and cut-down quantity were estimated using ISM. In the present study, ISM was applied to estimate the demand shortage due to gate valves, and then Imp_{PB} on RWT was estimated. The equation for Imp_{PB} on RWT is shown in Eq. (7).

$$impact_{pi}^{2st} = E_i \quad (7)$$

where $impact_{pi}^{2st}$: demand shortage of RWT for burst of pipe i (m^3/day); and E_i: assignment demand of segment included pipe i (m^3/day).

Imp_{PB} on RWT is the demand assigned by a segment where related pipes are included. The assignment segment demand in the segment means the water supply quantity that the segment supplies to other segments, as well as to itself. Thus, if a pipe is burst in a segment, the assignment segment demand is the impact on RWT, and the impact of all the pipes in the segment is the assignment demand in the segment. The assignment segment demand is estimated as shown in Eq. (8).

$$E_i = d_i + \sum_{j \in D_i} e_i(j) \quad (8)$$

where E_i: assignment demand of segment i (m^3/day); d_i: demand of segment i (m^3/day); $e_i(j)$: demand of sub-segments dependent on the segment i (m^3/day); and D_i: sub-segments of segment i.

2.4. Development of the WSR assessment model

WSR is the demand shortage of $Prob_{PB}$, and is calculated as the product of $Prob_{PB}$ and Imp_{PB}. The WSR of each pipe is calculated as shown in Eq. (9).

$$Risk_{pi} = prob_{pi} \times \left\{\left(impact_{pi}^{1st} \times T^{1st}\right) + \left(impact_{pi}^{2st} \times T^{2st}\right)\right\} \quad (9)$$

where $Risk_{pi}$: WSR of pipe i (m^3/year); $prob_{pi}$: $Prob_{PB}$ of pipe i (no./year); $impact_{pi}^{1st}$: demand shortage in LDT for burst of pipe i (m^3/day); $impact_{pi}^{2st}$: demand shortage in RWT for burst of pipe i (m^3/day); T^{1st}: duration of LDT (day); and T^{2st}: duration of RWT (day).

In order to estimate the WSR for each block, WSR values of pipes in the same block were averaged using Eq. (10).

$$Risk_b = \frac{\sum_{i=1}^{n} Risk_{pi}}{n} \quad (10)$$

where $Risk_b$: block WSR (m^3/year); and n: pipe number in block.

The concept of block WSR is necessary for conducting a relative comparison of the WRS values of unit blocks. Therefore, a relative comparison of WSR values between distribution blocks that have different numbers of pipes can be conveniently conducted.

3. Results and discussion

3.1. Results of assessment model development of $Prob_{PB}$

Logistic regression analysis was used to verify the statistical significance of each variable after selecting the values of independent variables that were significant (p value < 0.05), using Wald statistics in the forward selection method. The model with the highest prediction was selected. All the used variables significantly affected Prob_{PB}, as shown in Table 4.

After logistic regression analysis, the logistic regression coefficient (B) calculated for each independent variable corresponds to the unstandardized partial regression coefficient, in general multiple regression, and represents the intensity and direction of the effects of independent variables on dependent variables.

Using the logistic regression coefficient (B), Prob_{PB} is measured in Eq. (11).

$$Prob_{PB} = \frac{\exp(\beta_0 + \beta_1 x_1 + \cdots + \beta_k x_k)}{1 + \exp(\beta_0 + \beta_1 x_1 + \cdots + \beta_k x_k)}$$

$$Z = -3.156 + 0.290A + 0.037D - 0.147E + 0.060R + 0.039C \tag{11}$$

where $\beta_0 + \beta_1 + \cdots + \beta_k$: regression coefficient (B); $(\beta_0 + \beta_1 x_1 + \cdots + \beta_k x_k)$: Z; A: age, D: diameter, E: depth, R: road, and C: area characteristic.

3.2. Assessment results of LDT and RWT estimation model

For the significance test of each coefficient though hierarchical input in multiple regression analysis, independent variables that were significant (p value < 0.05) were selected. As a result, as shown in Table 5, it was shown that input independent variables affected pipe burst time significantly. Therefore, since the developed model was considered to be suitable for this study, it was used to obtain the coefficients of the multiple regression to calculate LDT and RWT by pipe burst.

Table 4
Variables in the equation

Variable	B	SE	Wald	Sig.	Exp (B)
Age	0.290	0.011	703.542	0.000	1.336
Diameter	0.037	0.016	5.023	0.025	1.037
Depth	−0.147	0.020	52.254	0.000	0.863
Road	0.060	0.025	5.891	0.015	1.062
Area characteristic	0.039	0.015	6.518	0.011	1.040
Constant	−3.156	0.103	945.391	0.000	0.043

Notes: B: logistic regression coefficient, SE: standard error, Wald: Wald statistics, Sig.: significant level, Exp (B): odds ratio.

The equation used to calculate the pipe burst repair time by unstandardized regression coefficients produced for each independent variable in multiple regression is shown in Eq. (12).

$$Y = -1.450 + (4.741 \times R) + (0.912 \times L) \tag{12}$$

where Y: total duration of LDT and RWT (day); R: 1. footway, 2. 2 lane road, 3. ≥ 4 lane road; and L: 1. 0~10 year, 2. 11~20 year, 3. 21~30 year, 4. over 31 year.

3.3. Assessment results of WSR model

3.3.1. Assessment results of the WSR of each pipe

The assessment results of the WSR of each pipe in A2 Block are shown in Fig. 2.

All the Prob_{PB}, pipe length, LDT impact, and RWT impact were considered in the WSR of each pipe. The WSR of 0.372 m^3/year for #1 pipe in A2 Block represents the possibility of a demand shortage (0.372 m^3) due to pipe burst occurring once a year. As above, the concept of WSR is an indicator for the water supply management in terms of consumers' perspective, while simultaneously considering Imp_{PB}, not for the water supply management in terms of provider's perspective, but for Prob_{PB} in terms enhancing the revenue water ratio.

3.3.2. Assessment results of block WSR

On the assumption that the leakage hole in each pipe is 1 cm^2, the block WSR of A2 Block was calculated to be 1.507 m^3/year in the case of leakage. This risk is the average WSR of pipes in the same block, which indicates that pipe burst occurs approximately once a year in a pipe and that a demand shortage with a probability of 1.507 m^3 occurs. Fig. 3 shows the results produced after estimating the block WRS of LDT, block WRS of RWT, and total block WRS values.

With increasing pipe leakage, the block WSR of LDT rapidly increases whereas the block WSR of RWT remains invariable.

On the other hand, the orifice (Eq. (2)) was applied to estimate the leakage quantity. The orifice equation shows that the leakage quantity is proportional to the water pressure raised to the power of 0.5. However, when the leakage quantity was estimated using the

Table 5
Coefficients of the multiple regression model

Model	Unstandardized coefficients		Standardized coefficients		
	B	SE	*β*	*t*	Sig.
Constant	−1.450	1.527		−0.949	0.344
Road	4.741	0.594	0.559	7.985	0.000
Age	0.912	0.358	0.178	2.549	0.012

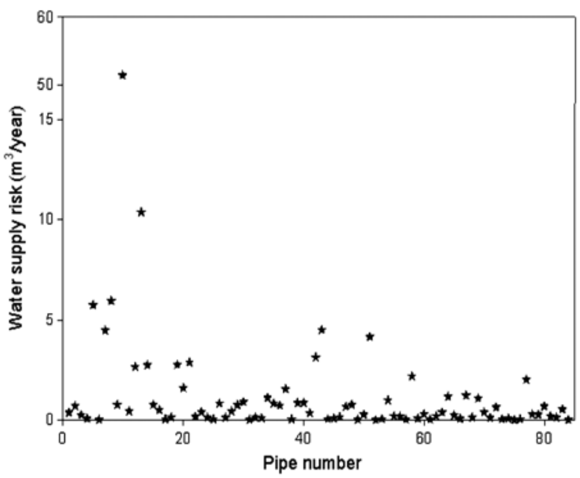

Fig. 2. WSR according to pipe number for block A2.

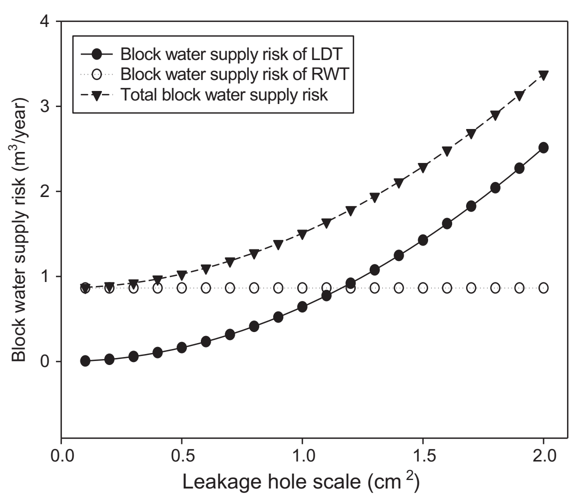

Fig. 3. Effect of leakage hole scale on the block WSR for block A2.

equation where the leakage quantity is proportional to the water pressure raised to the power of 1.15, the block WSR was greatly increased to 2.291 m^3/year because the leakage quantity increased with increasing water pressure index increased.

Accordingly, the increased leakage quantity of each pipe augmented WSR and, in particular, affected the block WSR of LDT. Fig. 4 shows the results produced after estimating the block WSR based on the number of installed gate valves when one gate valve was additionally installed to each specific site and there were already 54 valves in A2 Block. The size of the leakage hole was 1 cm^2.

The block WSR was reduced with increasing number of installed gate valves and, in particular, the block WSR of RWT was decreased, probably because the increased number of gate valves dispersed Imp_{PB} on RWT. On the other hand, since the block WSR of LDT is not related with the presence or absence of gate valves, the number of gate valves had no effect.

3.4. *Analysis of effects according to priority determination of pipe replacement construction*

The cost of pipe replacement to improve the water supply, based on $Prob_{PB}$, Imp_{PB}, and WSR analysis, for the block WSR variation about the three analytical methods, is shown in Table 6.

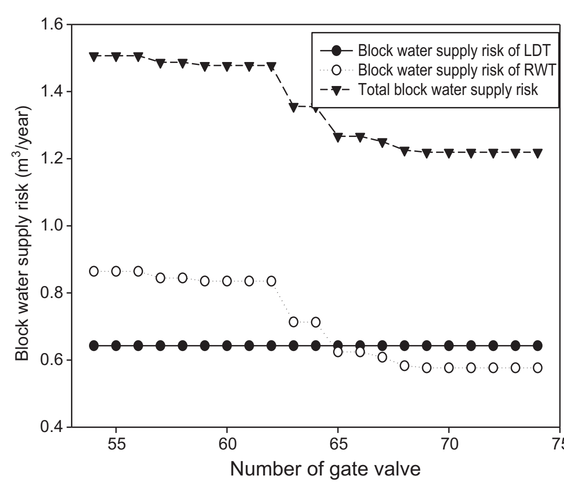

Fig. 4. Effect of gate valve number on the block WSR for block A2.

These values are converted ones by 1 m. Therefore, for short pipe lengths, the cost was calibrated under the assumption using Eq. (13).

$$\begin{cases} PR_{cost} = DR_{cost} & P_L \geq 12m \\ PR_{cost} = DR_{cost} \times \frac{12}{P_L} & P_L < 12m \end{cases} \quad (13)$$

where PR_{cost}: pipe replacement cost (won); DR_{cost}: pipe replacement cost according to diameter (won); and P_L: pipe length (m).

The top 15 items, of the $Prob_{PB}$ of each pipe in A2 Block, total impacts of LDT and RWT, and WSR are shown in Table 7. Thus, pipe replacement was conducted based on the priority order.

Approximately 2.6 billion won was appropriated as the total cost of the replacement project for the 84 pipes in A2 Block. Approximately 10% of the total cost was allocated for the replacement work, as shown in Table 7. In order to conduct the pipe replacement, a method was used to set the post-replacement $Prob_{PB}$ at 0.2/km/year; the results are shown in Table 8.

Under the condition that all 84 pipes in the subject region are replaced, the block WSR reduction effect in comparison with cost input was calculated to be 0.461 m^3/year/billion won. After conducting pipe replacement based on three criteria, $Prob_{PB}$, Imp_{PB}, and WSR, the block WSR reduction was found to be 0.524 m^3/year/billion won, 2.163 m^3/year/billion won, and 2.173 m^3/year/billion won, respectively. The results of the replacement performed based on the three criteria revealed a high block WSR reduction effect compared with the average replacement cost. In particular, the block WSR reduction in pipe replacement based on the WRS criterion was the most effective.

In the estimation of the pipe replacement cost in this study, fixed expense was considered when a replacement construction of less than two pipe units was planned. However, in practice, taking into account the fact that all the construction expenses except material expenses are included in the one-day

Table 6
Unit cost of replacement according to pipe diameter

Diameter (mm)	Replacement cost (won/m)	Diameter (mm)	Replacement cost (won/m)
80	316,500	250	466,860
100	348,000	300	514,790
150	389,050	350	580,130
200	425,800	400	627,000

Source: Water resources engineering corporation (2013).

Table 7
Results of priority according to $Prob_{PB}$, impact, and WSR

	$Prob_{PB}$		Total impact		WSR	
Priority	Pipe number	Length (m)	Pipe number	Length (m)	Pipe number	Length (m)
1	12	30.79	13	14.95	10	409.28
2	3	6.01	7	7.88	13	14.95
3	8	81.33	1	1	8	81.33
4	43	390.48	9	5.46	5	419.54
5	19	151.2	11	3.28	43	390.48
6	10	409.28	10	409.28	7	7.88
7	6	1.09	12	30.79	51	114.2
8	7	7.88	8	81.33	42	175.34
9	13	14.95	29	19.98	21	215.24
10	9	5.46	16	73.48	19	151.2
11	11	3.28	44	1.45	14	221.35
12	4	6.55	37	42.96	12	30.79
13	17	4.6	51	114.2	58	100.34
14	5	419.54	71	4.8	77	91.73
15	42	175.34	70	12.73	20	152.4

Table 8
Comparison results with $Prob_{PB}$, impact, and WSR

	$Prob_{PB}$		Total impact		WSR	
Priority	Pipe number	Replacement cost (won)	Pipe number	Replacement cost (won)	Pipe number	Replacement cost (won)
1	12	19,305,330	13	9,373,650	10	256,618,560
2	3	26,829,330	7	16,897,650	13	265,992,210
3	8	77,823,240	1	21,566,250	–	–
4	43	229,739,484	9	29,090,250	–	–
5	19	294,120,444	11	36,614,250	–	–
6	–	–	10	293,232,810	–	–
Block WSR	1.353 (m^3/year)		0.873 (m^3/year)		0.929 (m^3/year)	
Reduced risk/cost	0.524 (m^3/year/billion won)		2.163 (m^3/year/billion won)		2.173 (m^3/year/billion won)	

construction cost of replacing even one pipe unit, greater effects were found to have occurred.

Accordingly, WSR that considers the two indexes simultaneously (the $Prob_{PB}$ index, with which water supply management is conducted in terms of the providers' perspective, and the Imp_{PB} index, with which water supply management is conducted in terms of the consumers' perspective) was appropriate for application.

4. Conclusion

A WSR assessment model of a water distribution network was developed, in which WSR was defined as the product of $Prob_{PB}$ and Imp_{PB}. A water-pipe network management index that considers the consumers' interests rather than the providers' interests was proposed. Analysis of the study results revealed that the components of WSR could be classified into $Prob_{PB}$ and the impact of LDT and of RWT, and, further, that each component was affected by the influencing factors of the water supply network. In detail, networking factors such as emergency pipes connected to adjacent blocks, and other pipe-related factors such as variation of pipe diameter, were related to the impact of LDT among the WSR components, the number and locations of gate valves were related to the impact of RWT, and pipe replacement was related to $Prob_{PB}$. More accurate quantification of these results in follow-up studies will improve the management of water supply networks in terms of the consumers' perspective. In conclusion, consumers' needs cannot be satisfied by only using provider-oriented indexes such the revenue water ratio, and the concept of WSR is therefore essential to meet their needs. Thus, the management of water supply networks should be expanded to include the concept and methods of WSR, as developed in this study, in order to increase the effectiveness of water-pipe network management.

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