Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2019.23561

143 (2019) 126–136
March

A study on the reconstruction model for minimizing water supply risk in existing water distribution network

Taeho Choi[a], Dooyong Choi[a], Kibum Kim[b], Jayong Koo[b,*]

[a]*K-water Institute, Korea Water Resources Corporation, 125, Yuseong-daero, 1689 beon-gil, Yuseong-gu, Daejeon, 34045, Republic of Korea, emails: choistarth@kwater.or.kr (T. Choi), dooyong@kwater.or.kr (D. Choi)*
[b]*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: jykoo@uos.ac.kr (J. Koo), kumbo88@hanmail.net (K. Kim)*

Received 4 September 2018; Accepted 1 December 2018

ABSTRACT

This study details the development of a reconstruction model for reducing water supply risk (WSR) in an existing water distribution network (WDN). This development included additional gate valves for reducing the impact of a burst pipe (Imp_{PB}), additional emergency pipes for adjacency block, and pipe replacement to reduce the probability of a burst pipe ($Prob_{PB}$). The developed model was applied to the study area, giving a block WSR in the reconstructed network of 0.471 m^3/year, with a possible input budget of about KRW 140 million (4.5% of the maximum cost for reconstruction); 1,000 KRW = 0.92 USD = 0.69 EUR, 31 Dec 2012. This constituted a decrease of block WSR by 68.7% compared with that of the existing pipe network. The benefit cost for WSR reduction was defined as shown in Scenarios 1–4 at respective ratios of KRW 40,000/m^3, KRW 60,000/m^3, KRW 80,000/m^3, and KRW 100,000/m^3. Results show that higher the benefits of reducing the WSR in existing WDNs, more the chance for WSR reduction. On the other hand, if the benefit cost for WSR reduction is low, this indicates that it is not possible to actively reduce WSR. In other words, it is currently difficult to accurately convert the benefits of reduced WSRs. However, if such problems are solved in the future, it should be possible to establish more accurate budgets and plans can for minimizing WSR in existing WDNs.

Keywords: Additional gate valve; Pipe replacement; Reconstruction model; Water distribution network; Water supply risk

1. Introduction

When designing a water distribution network (WDN) with an optimal design method, several benefits can come into effect immediately. However, as time goes by, water demands change according to changes in water usage characteristics, and the possibility of pipe breakage increases due to pipe aging. For this reason, WDNs require constant maintenance. The water supply risk in a WDN depends on the condition of the pipes and the positions of the gate valves. As shown in Fig. 1, water supply risk can be reduced by installing additional gate valves, by installing additional emergency pipes for adjacent blocks, and by replacing pipes.

Here, additional emergency pipes reduce the influence of water supply risk (WSR) reduction on repair work time (RWT), while additional gate valves reduce the effect of leakage duration time (LDT). Pipe replacement also reduces probability of a burst pipe ($Prob_{PB}$). This study considers these three WSR reduction measures, sets an upper limit for the construction costs of reconstructing an existing WDN, and derives an optimal method for mitigating WSR in a water distribution/supply network.

2. Literature review

2.1. Additional emergency pipes

The city of Kobe, Japan, has built a large-scale water transmission tunnel and a high-capacity water transmission

* Corresponding author.

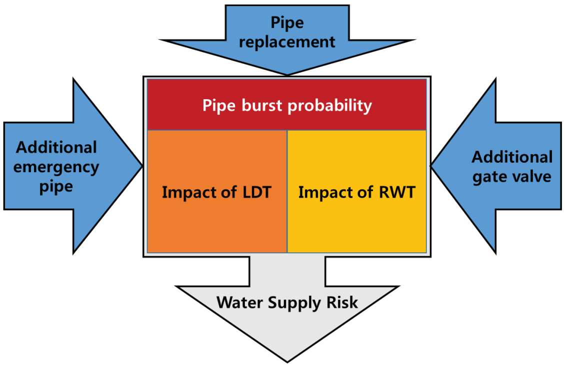

Fig. 1. Methods for WSR reduction for an existing WDN (LDT = leakage duration time, RWT = repair work time).

pipe to provide an emergency water supply and early recovery for disasters or emergency water cut-offs. In Tokyo, a water supply system without any water cut-offs is being constructed through the double connection of the raw water pipes and the network connection operations of the water distribution area, using water transmission pipes. In New York, the United States of America, the development of urban tunnels, which are alternative facilities, is being implemented in accordance with the need to rehabilitate aging facilities. New York has also maximized the efficiency of water supply by operating an interconnection facility to prevent water cut-off. Furthermore, in London, the United Kingdom, a ring main water distribution system is being used due to increases in water demands and leakage and breakage from aging pipes. Particularly, Kanakoudis [1] applied the methodology for the hierarchical analysis (in time and space) of the preventive maintenance policy of water supply networks, using water supply systems performance indices to the Athens and suggested the replacement and additional emergency pipe.

Likewise, efforts have been made overseas to improve service satisfaction through providing emergency water supplies and preventing water cut-off. In Korea, however, the introduction and implementation of plans for a water supply system without water cut-off are now at the beginning stage. Efforts to prevent water cut-off in the raw water/water transmission pipe network are currently limited to some cities in Korea. Model cases from out of sea are required to construct a systematic and well-planned water supply system devoid of water cut-offs. From this point of view, this study aims to minimize the WSR of the WDN through methods such as additional emergency pipes and new pipe installations.

2.2. Additional gate valves

In order to expand a water pipe network, to relocate a valve in its current state, and to install additional valves, it is necessary to distinguish the pros and cons for each gate valve. To do this, there is a need for objective criteria on topics such as the number of consumers affected by the isolation of a partial water pipe network, that is, an efficiency index; and the valve efficiency, which can be calculated by the range of pipes that can isolated for pipe breakage or other water pipe maintenance activities. Many studies have been conducted to resolve problems related to the determination of valve arrangement and efficiency.

Bouchart and Goulter [2] proposed a model to determine valve placement that minimized water loss in pipe failure. The model was restrictive, and assumed that water loss occurring at the time of pipe failure was limited to the damaged pipe. The effect of water loss on the remaining portion was not taken into account; the two valves were installed at each end of the pipe. Hoff [3] presented criteria for valve management and selection based on actual water pipe networks. Deb and Srinivas [4] conducted surveys and interviews with organizations that operate a wide range of actual water pipe networks to provide analytical criteria for evaluating the efficiency of water pipe networks based on relevance, reliability, and efficiency. In Korea, Seoung et al. [5] analyzed the leakage of a water pipe network through valve control. Lee et al. [6] proposed a network control valve search algorithm based on graph theory. In addition, studies to optimize the placement of gate valves in water pipe networks have been conducted by Reis et al. [7], Ozger [8], and Araujo et al. [9].

In this study, it was found that additional gate valves can improve the efficiency and reliability of existing WDNs, as can be seen from the prior studies on optimal placement of gate valves. Hence, additional gate valve method is expected to be of great significance as a way to minimize the WSR.

2.3. Pipe renovation and replacement

The first attempts to develop models forecasting pipe break rates by statistically processing data from previous failures, took place in the late 1970s. Since then, research has been conducted by researchers such as O'Day, Kettler, Goulter, Walski, Pelliccia, Walter, Kazemi [10]. Particularly, Dandy et al. [11] suggested that the renovation and replacement of pipes should meet three important requirements: economic feasibility, stability, and water quality. The economic standard concerns minimizing expenditure, including breakdown and maintenance costs, so that the water distribution system operates efficiently. This clearly distinguishes between direct costs, which occur in water suppliers, and indirect costs, which occur in the community. Costs can be divided into capital costs, maintenance costs, operating costs, and damage costs. The capital cost refers to the cost of supplying and laying pipes. The maintenance cost is related to failures and repairs within the system. The operating cost includes the cost of operating the system, including the expense of the electricity used in the pump. The damage cost includes all costs that stem from pipe failure, such as property damage, user inconvenience, and loss of convenience facilities. The stability standard concerns maintenance of the performance of the system to provide satisfactory service, which is always required for all users. Quimpo and Shamsi [12], Li and Haimes [13], and Schneiter et al. [14] have all described the direct stability of the rehabilitation of the water distribution system.

The water quality standard takes into account changes in water quality resulting from the chemical properties of the water transferred due to aging pipes. In this study, to minimize the WSR in an existing WDN, the pipe renovation and replacement method that was used considered both economic feasibility and stability. As seen in preceding studies, additional emergency pipes, additional pipe installation, additional gate valves, renovation and replacement of pipes, can all reduce WSR in existing WDN.

In this study, these methods were applied to the WDN. The three methods of additional emergency pipes, additional gate valves, and pipe replacement were used to develop a reconstruction model for minimizing WSR in the existing WDN.

3. Research methods

The study aimed to develop a reconstruction model for reducing WSR in an existing WDN. For this, additional emergency pipes, additional gate valves, and pipe replacement were considered within a range that met restrictions on the reconstruction cost.

First, the current block WSR for the existing WDN was calculated. Three reconstruction methods were used. The figure was applied to calculate the cost and expected reduction in block WSR for the existing WDN, where the flow rate, water pressure at nodes, and installation conditions are met in the WDN. Next, for each of the three reconstruction methods, the cost-effectiveness of the reduced block WSR was analyzed to determine which is the most optimal. In this way, the method of maximizing the cost-effectiveness was sequentially applied to the existing WDN to determine the optimal WDN reconstruction scenario.

The reconstruction model developed in this study is based on a WSR assessment model developed by Choi and Koo [15], and can be described as another approach of "optimized design for new WDNs using the WSR assessment model" applied by Choi et al. [16]. The application area of the existing WDN reconstruction model developed in this study is also the same as Block A2, WDN District K. The procedure of the developed model is as shown in Fig. 2.

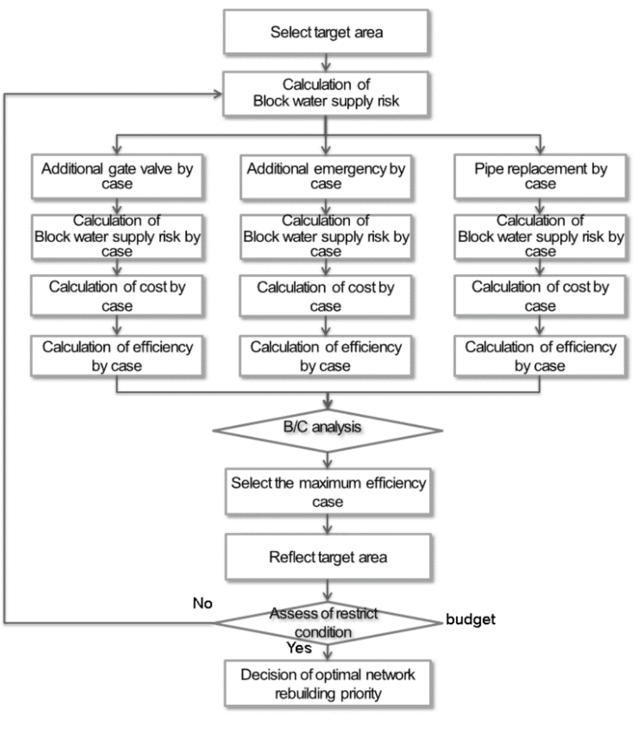

Fig. 2. Flow chart for rebuilding model development of existing WDNs.

3.1. Case study area

To estimate the WSR, this study used geographic information system (GIS) data for total pipes, registers of leakage recovery, and water supply data from Block A2, WDN District K, City S, and applied construction standard production unit system and related construction data to estimate embedment costs per pipe diameter. This area included 84 pipes, the number of connections was 237, and the total length of pipes was 5,706 m. The total demand of this area was 813.34 m^3/d, and Block A2 was adjacent to Blocks A1, B3, B5, and C7.

3.2. Definition of WSR

The block WSR was estimated using the WSR estimation model defined by Choi and Koo [15]. The block WSR estimation method can be described using the following equations. WSR is the demand shortage of the Prob_{PB}, and is calculated as the product of Prob_{PB} and impact of a burst pipe (Imp_{PB}). A Prob_{PB} function was produced by applying logistic regression. Here, logistic regression was used to obtain the Prob_{PB} for each pipe unit, whereas previous statistical approaches have predicted bursts in pipe groups that have similar characteristics. In addition, Imp_{PB} is calculated into the impact on LDT, from when the pipe bursts to gate-valve closure, and on RWT, from gate-valve closure to repair completion. Therefore, the WSR of each pipe is calculated as shown in Eq. (1) as follows:

$$\text{Risk}_{pi} = \text{prob}_{pi} \times \left\{ \left(\text{impact}_{pi}^{1\text{st}} \times T^{1\text{st}} \right) + \left(\text{impact}_{pi}^{2\text{st}} \times T^{2\text{st}} \right) \right\} \tag{1}$$

where Risk_{pi} is the WSR of pipe i (m^3/year); prob_{pi} is the Prob_{PB} of pipe i (number/year); $\text{impact}_{pi}^{1\text{st}}$ is the demand shortage in LDT for when pipe i bursts (m^3/d); $\text{impact}_{pi}^{2\text{st}}$ is the demand shortage in RWT for when pipe i bursts (m^3/d); $T^{1\text{st}}$ is the duration of LDT (d); and $T^{2\text{st}}$ is the duration of RWT (d).

In order to estimate the WSR for each block, the WSR values for pipes in the same block were averaged using Eq. (2) as follows:

$$\text{Risk}_b = \frac{\sum_{i=1}^{n} \text{Risk}_{pi}}{n} \tag{2}$$

where Risk_b is the block WSR (m^3/year) and n is the number of pipes in the block.

The WSR of a WDN can be defined as the product of Prob_{PB} and Imp_{PB}. Prob_{PB} is estimated by logistic regression analysis, using the factors affecting pipe bursts and records of previous pipe bursts. However, since the pipes in case study area are new, Prob_{PB} was set at 0.2 (case/km/year). This is the minimal value among Prob_{PB} values for all pipes in the case study area. The WSR assessment model of the WDN was also expressed as the product of Prob_{PB} and Imp_{PB}. Imp_{PB} was classified into an impact index of LDT and an impact index of RWT. The sum of these two indexes was treated as the total impact index for a given burst pipe. The assessment model was developed to estimate the impacts of water supply cut-offs and water supply cut-downs based on valve installation positions, pipe positions, and emergency connective pipes. Prob_{PB} was calculated using logistic regression analysis, and the impact of LDT was calculated using the EPANET 2.0 emitter. The demand shortage at all nodes was calculated to estimate the impacts after leakage production, based on the assumption that the leakage amount is proportional to the pressure of the node reached by each pipe. The impact on RWT was calculated using interpretive structural modeling and a concept of a "segment" based on the gate-valve boundary. To repair a pipe burst, the closest gate valve is closed, and "segments" are then made. The Imp_{PB} on RWT was estimated by calculating the total demand shortage of "segments" caused by gate valves that were closed for pipe repair. The LDT and RWT for each pipe were estimated by multiple regression analysis, and were then multiplied by the impacts of LTD and RWT in order to quantify the volume.

3.3. WSR reduction by additional emergency pipes

3.3.1. Calculation of WSR reduction by additional emergency pipes

The reduction in WSR achieved by using additional emergency pipes was estimated by calculating the difference between the block WSR estimation in the existing WDN and the block WSR estimation once additional emergency pipes had been added to adjacent blocks.

The adjacent blocks surrounding Block A2, which is the study area, were Block A1, Block B3, Block B5, and Block C7. Five points for adding emergency pipes were selected, considering factors such as water pressure conditions, and possible emergency pipe connectivity. In the case of emergency pipe connections, since the pipes were new, the Prob_{PB} was set as 0.2 cases/km/year, which was the assumed minimum value. The positions of the five emergency pipes in the study area are shown in Fig. 3. Information is as shown in Table 1.

To simulate the additional emergency pipes in the model, the nodes of the emergency pipes in the pipe network were converted into reservoirs. The total head of each reservoir

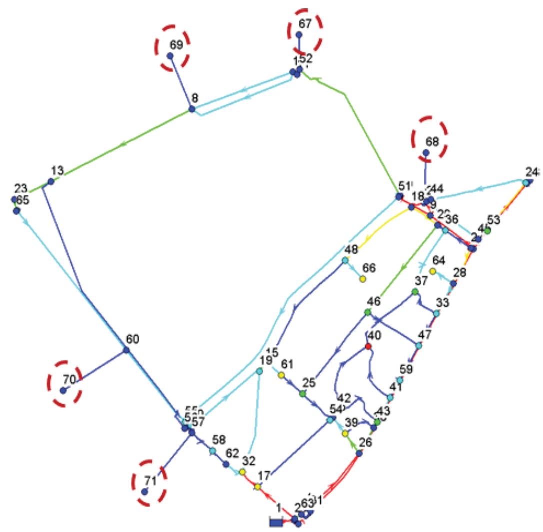

Fig. 3. Additional locations for emergency pipes in Block A2, denoted by dashed red lines.

added to the pipe network was the same as the hydraulic pressure of the corresponding node. The diameter of each emergency pipe was the same as that of the pipe connected to the node of the adjacent block. The extension of the emergency pipe was calculated as the distance between the adjacent block and the node, where obstacles such as roads and buildings were considered.

In order to estimate the WSR reduction due to the addition of the emergency pipes, the block WSR in the existing WDN needed to be estimated. The block WSR for each additional emergency pipe could then be calculated as shown in Eq. (3) as follows:

$$\Delta\text{Risk}_b = \frac{\sum_{i=1}^{n}\text{Risk}_{pi}^{\text{before}}}{n} - \frac{\sum_{i=1}^{n+1}\text{Risk}_{pi}^{\text{after}}}{n+1} \tag{3}$$

where ΔRisk_b is the reduction in block WSR resulting from additional emergency pipes (m^3/year); $\text{Risk}_{pi}^{\text{before}}$ is the WSR of the ith pipe before additional emergency pipe (m^3/year); $\text{Risk}_{pi}^{\text{after}}$ is WSR of the ith pipe after additional emergency pipes (m^3/year); and n is the number of pipes.

3.3.2. Calculation of the cost for additional emergency pipes

When installing additional emergency pipes, gate valves also need to be installed to stabilize the water supply. This means that the cost for additional emergency pipes can be calculated as the sum of pipe installation cost and the cost of additional gate valves. The costs for pipe and additional gate valves are shown in Tables 2 and 3, respectively.

Table 1
Information of additional emergency pipe

Emergency pipe number	Adjacency block	Diameter (mm)	Length (m)	Total head (m)
85	B3	200	8	96.55
86	A1	150	28	96.57
87	B3	200	50	96.44
88	B5	200	32	96.45
89	C7	150	32	96.45

Table 2
Total laying cost for each pipe diameter

Diameter (mm)	Cost (won/m)
80	148,200
100	156,700
150	183,500
200	205,600
250	235,300
300	264,800
350	293,200
400	314,900

Table 3
Total laying cost for each valve diameter

Diameter (mm)	Cos*t* (won)
80	1,782,121
100	1,926,134
150	2,499,089
200	2,938,469
250	3,863,459
300	5,489,096
350	7,079,579
400	9,292,996

3.3.3. Cost-effectiveness calculation for the additional emergency pipes

The efficiency of the additional emergency pipes was calculated by using the ratio of the cost of the additional emergency pipes to the block WSR reduction. The calculation method was selected in descending order of efficiency using Eq. (4) as follows:

$$e^i = \frac{\Delta \text{Risk}_b^i}{\text{Cost}^i} \tag{4}$$

where e^i is the efficiency achieved by adding the *i*th emergency pipe; ΔRisk_b^i is the reduction of block WSR achieved by adding the *i*th emergency pipe (m^3/year); and Cost^i is the cost of adding the *i*th emergency pipe (in million won).

3.4. WSR reduction by including additional gate valves

3.4.1. Calculation of WSR reduction by including additional gate valves

The reduction of the block WSR achieved by the inclusion of additional gate valves was calculated by using the difference between the block WSR of the existing WDN and the block WSR calculated once the additional gate valves were included.

There are currently 54 gate valves in Block A2, and 36 minimum isolation zones are provided by the gate valves installed. A total of 165 gate valves can be installed in the block, except for spots that are unavailable for installation. Therefore, currently, 111 gate valves can be installed.

Gate valves were added to each of these 11 locations. In each case, the block WSR was assessed and the block WSR reduction achieved by installing the additional gate valve was calculated. The reduction in block WSR by installing the additional gate valves was calculated following Eq. (5) as follows:

$$\Delta \text{Risk}_b = \frac{\sum_{i=1}^{n} \text{Risk}_{pi}^{\text{before}}}{n} - \frac{\sum_{i=1}^{n} \text{Risk}_{pi}^{\text{after}}}{n} \tag{5}$$

where ΔRisk_b is the reduction of block WSR by the installation of additional gate valves (m^3/year); $\text{Risk}_{pi}^{\text{before}}$ is the WSR of the *i*th pipe before the instillation of the additional gate valve (m^3/year); $\text{Risk}_{pi}^{\text{after}}$ is the WSR of the *i*th pipe after the instillation of the additional gate valve (m^3/year); and *n* is the number of pipes.

3.4.2. Calculation of cost of additional gate valves

The cost of additional gate valves is shown in Table 3.

3.4.3. Cost-effectiveness calculation of additional gate valves

The efficiency of the additional gate valves were calculated based on the ratio of block WSR reduction to cost for each valve. Priority was selected using Eq. (6) as follows:

$$e^i = \frac{\Delta \text{Risk}_b^i}{\text{Cost}^i} \tag{6}$$

where e^i is the efficiency achieved by adding the *i*th gate valve; ΔRisk_b^i is the reduction of block WSR by adding the *i*th gate valve (m^3/year); and Cost^i is the cost of adding the *i*th gate valve (million won).

3.5. WSR reduction by pipe replacement

3.5.1. Calculation of WSR reduction achieved by pipe replacement

The reduction of the block WSR achieved by pipe replacement was estimated by using the difference between the block WSR of the existing WDN and the block WSR calculated after pipe replacement. For the calculation of block WSR after pipe replacement, the Prob_{PB} was assumed to be 0.2 cases/km/year.

A total of 84 pipes are currently buried in Block A; pipe replacement was considered for each of these 84 pipes.

Therefore, the pipe WSR was assessed for each case, and using this, the reduction of the block WSR after pipe replacement was calculated. The calculation of block WSR reduction by pipe replacement is shown in Eq. (7) as follows:

$$\Delta \text{Risk}_b = \frac{\sum_{i=1}^{n} \text{Risk}_{pi}^{\text{before}}}{n} - \frac{\sum_{i=1}^{n} \text{Risk}_{pi}^{\text{after}}}{n} \tag{7}$$

where ΔRisk_b is the reduction of block WSR after pipe replacement (m^3/year); $\text{Risk}_{pi}^{\text{before}}$ is the WSR of the *i*th pipe before pipe replacement (m^3/year); $\text{Risk}_{pi}^{\text{after}}$ is the WSR of the *i*th pipe after pipe replacement (m^3/year); and *n* is the number of pipes.

3.5.2. Calculation of cost for pipe replacement

The cost for pipe replacement differs from the cost for pipe installation used in WDN optimization design. This is because the cost of pipe replacement also includes the cost of disposing existing pipes. Table 4 shows the pipe replacement costs per pipe used in this study.

These cost values are converted to KRW (1,000 KRW = 0.92 USD = 0.69 EUR, 31 Dec 2012) per m. Therefore, for short pipe lengths, the cost was calibrated using Eq. (8) as follows:

$$\begin{cases} \mathrm{PR}_{cost} = DR_{cost} P_L \geq 12\mathrm{m} \\ \mathrm{PR}_{cost} = DR_{cost} \times \dfrac{12}{P_L} P_L < 12\mathrm{m} \end{cases} \quad (8)$$

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

3.5.3. Calculation of cost-effectiveness of pipe replacement

The efficiency of pipe replacement was calculated using the ratio of the pipe replacement cost to the reduction in the block WSR. Priority was determined in descending order using Eq. (9) as follows:

$$e^i = \frac{\Delta \mathrm{Risk}_b^i}{\mathrm{Cost}^i} \quad (9)$$

where e^i is the efficiency of the ith pipe replacement; $\Delta\mathrm{Risk}_b^i$ is the reduction in block WSR by the ith pipe replacement (m^3/year); and Cost^i is the cost of the ith pipe replacement (million won).

3.6. Development of reconstruction model for the existing WDN

Additional emergency pipes, additional gate valves, and pipe replacement are all methods that can reduce the WSR for existing WDNs. However, each of these methods showed different results in cost and WSR reduction. In order to implement a reconstruction model for minimizing WSR in an existing WDN, these results should be considered altogether.

Therefore, in this study, the reviews of additional emergency pipes, additional gate valves, and pipe replacement were integrated, so that the priority for the reconstruction of the existing WDN was maximizing its cost-effectiveness.

Table 4
Unit cost of replacement according to pipe diameter

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

4. Results and discussion

4.1. Reduction of WSR by installing additional emergency pipes

Table 5 shows the reductions in block WSR achieved by individual emergency pipe installation. Considering the current state of the adjacent blocks in the study area, the possibility of water supply, and the construction cost, there are four blocks that could be operated in linkage with the case study area. After considering the construction constraints, such as cost and road conditions, it was found that in total five emergency pipes could be installed. In this study, it was possible to perform assessments on these five emergency pipes.

The reduction of the block WSR increased with increasing distance between the location of the emergency pipe and the inflow point of the existing WDN. This relationship may exist because if a pipe breakage accident occurs in Block A2, it can most effectively compensate for the shortage of demand due to pipe breakage.

Emergency pipe number 85 was the most efficient for decreasing the block WSR. The block WSR reduction at this time was 0.340 m^3/year, and the additional installation cost was KRW 4,583,269. The cost-effectiveness was 0.074 m^3/year/KRW 1 million. The results of comparisons between the WSR for each pipe in the network before and after the installation of emergency pipe number 85 are shown in Fig. 4.

Table 6 shows the efficiency of block WSR reduction achieved by the cumulative installation of emergency pipes in Block A2. This cumulative installation is the result of repetitive calculations to increase the efficiency of block WSR reduction.

Installing the emergency pipes cumulatively gradually decreased efficiency, and the most effective installation order for the emergency pipes was pipe number 85, followed by numbers 86, 88, 89, and finally 87.

Table 5
Estimate the reduction efficiency of block WSR according as additional emergency pipe

Emergency pipe number	Reduced block WSR (m^3/year)	Additional emergency pipe cost (won)	Additional gate valve cost (million won)	Reduced risk/cost (m^3/year/million won)	Rank
85	0.340	1,644,800	2,938,469	0.074	1
86	0.362	5,138,000	2,499,089	0.047	2
87	0.287	10,280,000	2,938,469	0.022	4
88	0.198	6,579,200	2,938,469	0.021	5
89	0.206	5,872,000	2,499,089	0.025	3

4.2. Reduction of WSR by installing additional gate valves

Currently, there are 54 gate valves installed in Block A2, controlling 36 minimum isolation zones. A total of 111 additional gate valves can be installed, further to those already installed. The addition of each gate valve increases the total number of minimum isolation zones in the WDN. With the increased number of minimum isolation zones, the water demand for each individual zone decreases, which can reduce the WSR of the RWT.

Therefore, these 111 additional gate values were installed in Block A2, and the WSR reduction and installation cost were analyzed.

Installing a gate valve between the 77th pipe and the 36th node reduced the block WSR by 0.062 m^3/year. It cost KRW 1,926,134 to install this gate, which featured the highest block WSR reduction effect compared with the gate valve installation cost. Fig. 5 shows the result of comparisons between the WSR for each pipe before and after the instillation of the additional gate valve located at the 77th pipe and 36th node.

The efficiency of block WSR reduction by installing additional gate valves was also calculated sequentially. This approach was expected to establish a more effective WSR reduction plan.

Table 7 shows block WSR reduction efficiency results for the cumulative installation of the gate valves in Block A2. This cumulative installation is the result of repetitive calculations to increase the efficiency of block WSR reduction.

Here, the additional gate valves are represented by the pipe number (*P*) and nodal number (*N*). Only the top 20 gate valves were used.

Installing the additional valves cumulatively gradually decreased the efficiency. This phenomenon occurs because each additional gate valve reduces the block WSR, while the cost of additional gate valves increases without significant fluctuations. In other words, if additional gate valves are installed to reduce the WSR in the existing WDN, the effect of reduced block WSR should be maximized compared with the gate valve installation cost.

4.3. Reduction of WSR by pipe replacement

To analyze the reduction of pipe WSR achieved by pipe replacement, the effect of replacing 84 pipes on WSR was analyzed, each with a $Prob_{PB}$ of 0.2 cases/km/year.

Replacing the 13th pipe reduced block WSR by 0.096 m^3/year; the pipe replacement cost was KRW 9,373,650. Fig. 6 shows the result of comparisons between the WSR for each pipe before and after the replacement of the 13th pipe.

The efficiency of block WSR reduction using sequential pipe replacement was also calculated; this approach is expected to result in a more effective plan to reduce block WSR.

Table 8 shows the efficiency of block WSR reduction achieved by cumulative pipe replacement in Block A2. This cumulative replacement is the result of repetitive calculations to increase the efficiency of block WSR reduction. Here, only the top 20 pipes were arranged for pipe replacement.

It was possible to calculate the block WSR reduction efficiency achieved by replacing pipes sequentially. By using this result, it is expected to establish a more effective plan to reduce WSR.

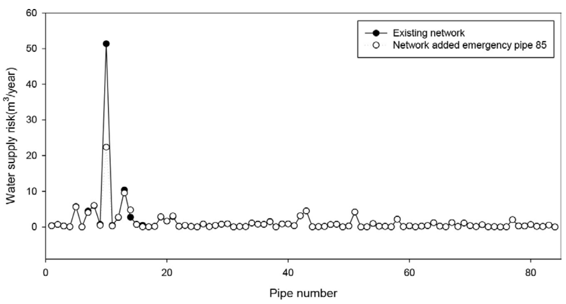

Fig. 4. Comparison of existing WSR with WSR after adding pipe 85.

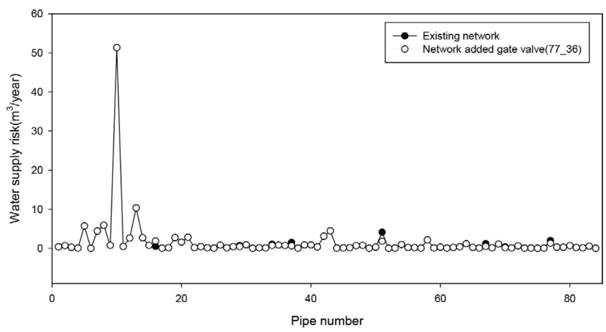

Fig. 5. Comparison of existing WSR with WSR after adding gate valve (77_36).

Table 6
Estimate the reduction efficiency of block WSR according as additional emergency pipe(accumulation)

Priority	Emergency pipe number	Block WSR (m^3/year)	Additional emergency pipe cost (won)	Additional gate valve cost (won)	Reduced risk/cost (m^3/year/million won)
–	Existing	1.507	–	–	–
1	85	1.167	1,644,800	2,938,469	0.0742
2	86	1.064	6,782,800	5,437,558	0.0084
3	88	1.013	13,362,000	8,376,027	0.0023
4	89	1.005	19,234,000	10,875,116	0.0003
5	87	1.001	29,514,000	13,813,585	0.0001

Table 7
Estimate the reduction efficiency of block WSR according as additional gate valve(accumulation)

Priority	Gate valve No. (P_N)	Block WSR (m^3/year)	Additional gate valve cost (won)	Reduced risk/cost (m^3/year/million won)
–	Existing	1.507	–	–
1	77_36	1.445	1,926,134	0.0324
2	37_29	1.371	4,425,223	0.0295
3	34_37	1.307	6,924,312	0.0256
4	51_18	1.264	9,423,401	0.0172
5	39_38	1.230	11,922,490	0.0136
6	58_26	1.198	14,421,579	0.0128
7	7_14	1.125	23,714,575	0.0079
8	10_4	1.081	33,007,571	0.0047
9	20_8	1.068	35,946,040	0.0044
10	18_11	1.054	38,884,509	0.0048
11	48_43	1.046	41,383,598	0.0032
12	8_53	1.020	50,676,594	0.0028
13	13_2	0.994	59,969,590	0.0028
14	36_33	0.987	62,468,679	0.0028
15	80_42	0.982	64,394,813	0.0026
16	47_47	0.976	66,893,902	0.0024
17	43_56	0.973	69,392,991	0.0012
18	64_46	0.971	71,892,080	0.0008
19	28_41	0.970	74,391,169	0.0004
20	26_25	0.969	76,890,258	0.0004

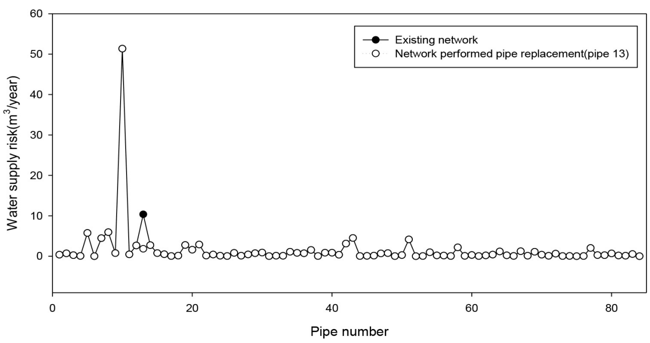

Fig. 6. Comparison of existing WSR with WSR after replacement of pipe 13.

4.4. Result of the development of a reconstruction model for the existing WDN

Thus far, the three methods to reduce WSR (additional gate valves, additional emergency pipes, and pipe replacement) have been analyzed individually. However, it is also necessary to consider the above three methods altogether. The results of analysis by repetitive calculation are detailed below.

First, applying the three methods to the existing WDN for the study area to their maximum extent, the costs are KRW 43,327,585 for 5 additional emergency pipes; KRW 447,190,289 for 111 additional gate valves; and KRW 2,604,230,189 for 84 pipe replacements. The total cost required would, therefore, be KRW 3,094,748,063. Assuming that the reconstruction cost for the existing WDN is 4.5% of the maximum cost, the most efficient reconstruction cases for the study area are shown in Table 9.

Applying the method with the biggest effect first and the method with the smallest effect last to Block A2 revealed that installing emergency pipe no. 85 first was the most efficient, followed by the installations of gate valve 77_36, gate valve 37_29, and emergency pipe no. 86. Prioritizing each of the three WSR reduction methods, the sequence was additional emergency pipes; additional gate valves; and pipe replacement in the adjacent block. Broadly, reconstructing the WDN following this sequence resulted in an efficiently decreased WSR.

Assuming a possible input budget of about KRW 140 million, which is 4.5% of the maximum reconstruction cost, the block WSR of the reconstructed pipe network is 0.471 m^3/year, which represents a reduction of 68.7%. This reduction is equivalent to the daily use of 195 people, which can be converted to 296 L of water supply per person (Lpcd) per day. Rebuilding the existing WDN in this way would, therefore, equate to the water cut-off for 1 d in 1 year for 195 people. The reduction effect of block WSR compared with the input cost of pipe replacement for all 84 pipes in Block A2 is

Table 8
Estimate the reduction efficiency of block WSR according as pipe replacement (accumulation)

Priority	Pipe replacement (P)	Block WSR (m^3/year)	Cost (won)	Reduced risk/cost (m^3/year/million won)
–	Existing	1.507	–	–
1	13	1.411	9,373,650	0.0102
2	7	1.389	16,897,650	0.0030
3	65	1.381	21,566,250	0.0017
4	70	1.372	26,518,857	0.0017
5	55	1.364	31,187,457	0.0017
6	18	1.356	36,297,057	0.0016
7	76	1.349	40,473,057	0.0016
8	46	1.341	45,713,561	0.0016
9	75	1.335	49,889,561	0.0016
10	71	1.327	54,558,161	0.0016
11	29	1.316	62,331,380	0.0015
12	44	1.309	66,999,980	0.0015
13	49	1.302	71,668,580	0.0014
14	24	1.295	76,778,180	0.0014
15	9	1.285	84,302,180	0.0013
16	52	1.279	89,118,619	0.0013
17	27	1.272	94,335,780	0.0013
18	1	1.262	101,859,780	0.0013
19	41	1.253	108,247,981	0.0013
20	61	1.246	114,161,541	0.0012

0.00046 m^3/year/KRW 1 million. Comparing this value with the efficiency of reconstructing the existing WDN, which is, showed that it was still valid up to the 20th reconstruction of the existing WDN.

However, the above results show only the relative effects of reconstructing the existing WDN. Therefore, to what point the WSR reduction should be continued is as yet unknown. If the budget for water management was sufficient, continuous WSR reduction measures could be taken. However, the economic feasibility cannot be sustained at low efficiency. Hence, a cost/benefit analysis was adopted to determine how the economic scope of the WSR reduction measures should be set. For this, to analyze the cost/benefit of WSR reduction, the benefits from WSR reduction needed to be converted into cost. When converting the benefits of additional emergency pipes, additional gate valves, and pipe replacement into cost values, it was assumed that the life expectancy of each component was 20 years, and the benefit cost for a 1 m^3 reduction in WSR was multiplied for calculation. However, the benefit cost for the WSR reduction was decided according to the scenario, since it contained qualitative values that the water consumer can feel. In other words, the benefit cost for WSR reduction was defined as shown in scenarios 1–4 at the respective ratios of KRW 40,000/m^3, KRW 60,000/m^3, KRW 80,000/m^3, and KRW 100,000/m^3 (Fig. 7).

In the case of scenario 1, as shown in Fig. 7, the reduction of WSR in the existing WDN was most efficient up to the 12th ranking. In the case of scenario 2, the same was true up to the 14th ranking. This means that higher the benefits of reducing the WSR in existing WDNs, the more chance there is for WSR reduction. On the other hand, if the benefit cost for WSR reduction is measured to be low, this indicates that it is not possible to actively reduce the WSR. Therefore, it appears that the WSR in the WDN can be effectively reduced within a given budget, if these results are utilized.

5. Conclusions

This study presents in details a reconstruction model for reducing WSR in an existing WDN. For this, three methods were considered: installing additional gate valves (which reduced the Imp_{PB}), installing additional emergency pipes to adjacent blocks, and performing pipe replacement (which reduced $Prob_{PB}$).

Applying the developed model to the study area achieved a block WSR in the reconstructed network of 0.471 m^3/year. With a possible input budget of about KRW 140 million (4.5% of the maximum cost for reconstruction), this indicated a decrease of block WSR by 68.7%, compared with that of the existing pipe network. The benefit cost for WSR reduction for

Table 9
Result of WDN rebuilding model for Block A2(accumulation)

Priority	Method	Location (x_y)	Block WSR (m^3/year)	Cost (won)	Reduced risk/cost (m^3/year/million won)
–	Existing	Existing	1.507	–	–
1	Additional emergency pipe	85	1.167	4,583,269	0.0742
2	Additional gate valve	77_36	1.064	7,082,358	0.0412
3	Additional gate valve	37_29	0.965	9,581,447	0.0396
4	Additional emergency pipe	86	0.776	21,801,805	0.0155
5	Additional gate valve	34_37	0.75	24,300,894	0.0104
6	Additional gate valve	51_18	0.731	26,799,983	0.0076
7	Pipe replacement	13	0.667	36,173,633	0.0068
8	Additional gate valve	39_38	0.651	38,672,722	0.0064
9	Additional gate valve	58_26	0.638	41,171,811	0.0052
10	Additional gate valve	7_14	0.595	50,464,807	0.0046
11	Additional gate valve	10_4	0.561	59,757,803	0.0037
12	Additional gate valve	20_8	0.554	62,696,272	0.0024
13	Additional emergency pipe	88	0.519	84,434,299	0.0016
14	Pipe replacement	7	0.497	101,331,949	0.0013
15	Additional gate valve	18_11	0.494	104,270,418	0.0010
16	Additional gate valve	48_43	0.492	106,769,507	0.0008
17	Additional gate valve	8_53	0.485	116,062,503	0.0008
18	Additional gate valve	13_2	0.478	125,355,499	0.0008
19	Additional gate valve	36_33	0.476	127,854,588	0.0008
20	Additional gate valve	80_42	0.475	129,780,722	0.0005
21	Additional gate valve	47_47	0.474	132,279,811	0.0004
22	Additional gate valve	43_56	0.473	134,778,900	0.0004
23	Additional gate valve	64_46	0.472	137,277,989	0.0004
24	Additional gate valve	28_41	0.471	139,777,078	0.0004

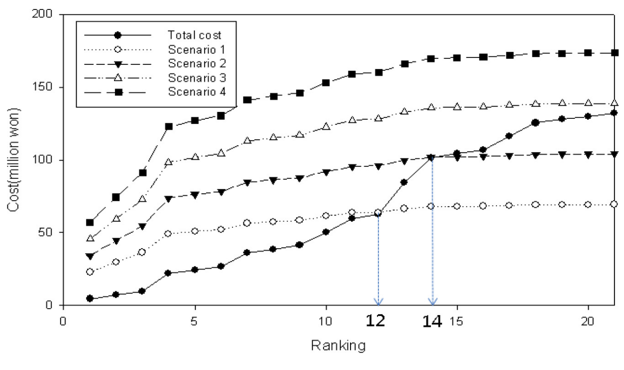

Fig. 7. WSR reduction results of WDN rebuilding models for each scenario.

scenarios 1 through 4 were KRW 40,000/m^3, KRW 60,000/m^3, KRW 80,000/m^3, and KRW 100,000/m^3, respectively. The results showed that higher the benefits of reducing the WSR in existing WDNs, the more chance there is for WSR reduction. If the benefit cost for WSR reduction is measured to be low, however, it may not be possible to actively reduce WSR. In other words, it is difficult to accurately quantify the benefits of reduced WSRs at the present time. However, in the future it should be possible to establish more accurate budgets and plans to minimize WSR in existing WDNs.

The model developed in this study proved that the design, evaluation, and maintenance of water supply networks, are the most basic and most important factors to both managers and consumers. In addition, it was found that the effects of these components of WSR can be divided into the $Prob_{PB}$, the influence of the LDT, and the RWT. It was also found that the different parts of water supply networks can influence the respective components of WSR in different ways. In short, networking methods such as adjacent blocks, emergency pipes, and the changes in pipe diameter were found to influence the LDT, whereas changes in the number and position of gate valves were found to influence the RWT. pipe replacement, was found to influence $Prob_{PB}$. Further quantification of these results in the future should allow for more effective management of water supply networks, considering the aspects of consumers.

In conclusion, an approach that uses only supplier-oriented indicators such as water flow rates cannot meet the demands of improved user demand; the concept of WSR, which considers the consumers' position, is essential to meet this demand. Hence, the concept of water supply network management should be changed in the future, and the new concept developed in this study should be utilized to perform a more effective water supply network management in terms of its design, assessment, and maintenance.

Acknowledgment

This subject is supported by Korean Ministry of Environment as Global Top Project (2016002120005).

References

[1] V.K. Kanakoudis, Vulnerability based management of water resources systems, J. Hydroinform., 6 (2004) 113–156.
[2] F. Bouchart, I. Goulter, Reliability improvements in design of water distribution networks recognizing valve location, Water Resour. Res., 27 (1991) 3029–3040.
[3] J.W. Hoff, Maintenance Requirements of Valves in Distribution Systems, Annual Conference Proceedings AWWA, June 20–27, 1996, Toronto, Ontario, Canada.
[4] K. Deb, N. Srinivas, Multi-objective optimization using non-dominated sorting on genetic algorithms, Evol. Comp., 2 (1994) 221–248.
[5] C.H. Seoung, N.S. Park, S.H. Kim, J.H. Kim, Leakage analysis by optimal valve control in pipe system, Proc. Korean Society of Civil Engineers Conference, 1999, pp. 201–204.
[6] K.H. Lee, C.J. Oh, Y.D. Kang, Valve searching algorithm for pipeline control, J. Korean Soc. Water Wastewater, 15 (2001) 222–228.
[7] L.F.R. Reis, R.M. Porto, F.H. Chaudhry, Optimal location of control valves in pipe networks by genetic algorithm, J. Water Resour. Plann. Manage., 123 (1997) 317–326.
[8] S. Ozger, A Semi-pressure-driven Approach to Reliability Assessment of Water Distribution Networks, Ph.D. Dissertation of Arizona State University, 2003.
[9] L.S. Araujo, H. Ramos, S.T. Coelho, Pressure control for leakage minimisation in water distribution systems management, Water Resour. Manage., 20 (2006) 133–149.
[10] V.K. Kanakoudis, D.K. Tolikas, The role of leaks and breaks in water networks: technical and economical solutions, J. Water Supply: Res. Technol.-AQUA, 50 (2001) 301–311.
[11] G.C. Dandy, A.R. Simpson, L.J. Murphy, An improved genetic algorithm for pipe network optimization, Water Resour. Res., 32 (1996) 449–458.
[12] R.G. Quimpo, U.M. Shamsi, Reliability based distribution system maintenance, J. Water Resour. Plann. Manage., 117 (1991) 321–339.
[13] D. Li, Y.Y. Haimes, Optimal maintenance-related decision making for deteriorating water distribution systems-1. Semi-Markovian model for a water main, Water Resour. Res., 28 (1992) 1053–1061,
[14] C.R. Schneiter, Y.Y. Haimes, D. Li, J.H. Lambert, Capacity reliability of water distribution networks and optimum rehabilitation decision making, Water Resour. Res., 32 (1996) 2271–2278.
[15] T.H. Choi, J.Y. Koo, A water supply risk assessment model for water distribution network, Desal. Wat. Treat., 54 (2015) 1410–1420.
[16] T.H. Choi, C.H Bae, H.S. Shin, J.Y. Koo, Optimal design of a new water distribution network using a water supply risk assessment, Desal. Wat. Treat., 65 (2017) 153–162.