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Determining Optimal Locations for Rainwater Storage Sites with the Goal of Reducing Urban Inundation Damage Costs

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Abstract

Because of climate change, severe rainfall events that lead to lowland flooding and inundation problems are occurring more frequently, especially in urban areas, which have high population densities. In order to prevent inundation of urban areas, authorities in the Korean Government have set up integrated flood management plans and established spatial targets for rainfall runoff. These disaster prevention plans include measures such as improvements to the sewer pipe capacity and the construction of downstream pump stations, rainwater storage sites, and infiltration facilities. The main purpose of pervious design plans is to reduce the flood volume in target areas, and this research presents a new method for developing rainwater storage design plans while considering potential flood damage costs in urban areas. The new planning method for storage facility design was applied to a single watershed in the Sintaein basin in the city of Jeongeup, Jeonbuk, South Korea. The results indicated that flood damage costs could be reduced when this new concept for determining the location of storage facilities is used.

Keywords: *flood damage costs, rainwater storage, off-line reservoir, optimal location, flood prevention*

1. Introduction

Land development and urbanization have increased the amount impervious area in urban watersheds, which has exacerbated flooding problems. In addition, urban areas have high population densities and this increases the risks for flood related injuries and property damage. To prevent urban inundation and flood damage, Korean authorities have set up integrated flood management plans and structural disaster prevention plans that include measures to improve sewer pipe capacity and construct downstream pump stations, rainwater storage sites, and infiltration facilities. Off-line rainwater storage, in particular, is an attractive flood control technique that can be implemented in areas smaller than those needed for on-line rainwater storage. However, this means that a larger number of potential construction locations need be considered during the planning stage, whereby several storage sites will be built in several locations instead of a single storage site to reduce the flood volume in target areas. It is well known that flood volume and flood damage costs have a proportional relationship. However, within particular subdivisions of a whole watershed, this relationship can vary according to subdivision characteristics. For example, some subareas may incur heavy damage costs from a flood, whereas other subareas may incur very little despite all the subareas receiving the same flood volume. To account for this diversity, a new method to determine optimal rainwater storage site locations based on flood damage costs is proposed here.

Several studies have introduced methods for determining appropriate locations and sizes of rainwater storage sites. Behera *et al.* (1999) presented an optimization methodology for determining the design parameters of rainwater storage sites to minimize the construction, operation, and maintenance costs. Mousavi and Ramamurthy (2002) used discrete dynamic programming to determine the optimal size and location of a network of retention basins within a watershed. Multi-Objective Genetic Algorithms (MOGAs) were used to design a detention system distributed throughout a watershed that specified optimal storage site sizes and locations (Chung *et al.*, 2008). A new sub-surface detention/retention system was recently developed that could reduce the volume and flow rate of stormwater runoff and promote the recharging of groundwater (AL-Hamati *et al*., 2010). Analytical derivation of the probability distribution of the number and volume of overflows from a storm tank to a receiving water body was used for different and non-standard shapes of the probability distribution for the above-mentioned descriptors (Andrés-Doménech *et al*., 2010). Even more recently, numerous studies have presented optimal design plans for the location, parameters, and capacity of rainwater storage systems and put forth recommendations

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for their operation (Andrés-Doménech *et al*., 2012; Baek *et al.*, 2012; Ryu and Lee, 2012; Yazdi and Salehi Neyshabouri, 2012; Chill and Mays, 2013; Lim *et al*., 2014; Tao *et al*., 2014; Gaudio *et al.*, 2015; Lee *et al*., 2016).

2. Determination of Rainwater Storage Locations with Consideration of Flood Damage Costs

The primary objective of this research was to determine optimal locations for rainwater storage sites that will minimize flood damage costs instead of solely considering reductions in flood volume, which is the most common focus area of the methods listed above. To determine flood damage, regionalization of the sub-basins was carried out first because flood damage costs show a different relationship than flood volume, and this was done in accordance with the importance of regional resources and the morphological land surface characteristics (MOLIT, 2004). For this purpose, flood volume, flood area, and flood depth compiled from two-dimensional (2D) flooding simulations were determined for each of these sub-basins. To calculate flood damage costs from these results, the Multi-Dimensional Flood Damage Analysis (MD-FDA) method, which can derive the flood damage costs by using flood depth and regional information, was used. After that, a flood volume–flood damage cost relationship was obtained by fitting the data to regression curves. Potential storage facility locations were determined by considering the pipe network layout, flood characteristics, and land use information. Of the two types of storage, namely, on-line and off-line, off-line was used in this study. It should be noted that a size limit for the storage facilities was not considered in this study, which means that the storage volume could potentially be infinite, thus allowing for storage of most of the inflow from the sewer network. The rainfall-runoff process was simulated by the Storm Water Management Model (SWMM) by using various rainfall scenarios and storage facility locations. Two kinds of simulations were carried out, specifically, one in accordance with the conventional methods that focus on flood volume and one for the new method that focuses on flood damage costs. The results were then compared as shown in Fig. 1.

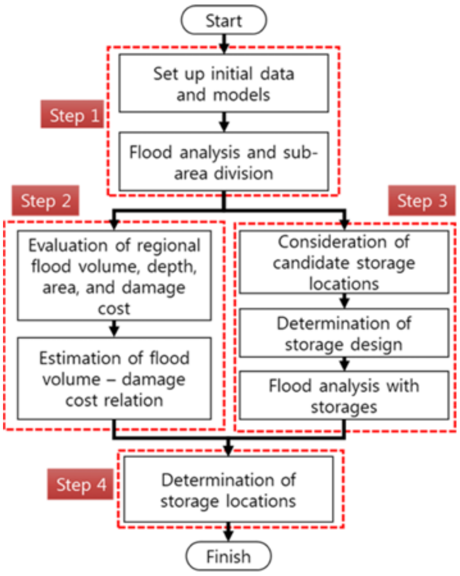

Fig. 1. Research Flow Chart

3. Multi-Dimensional Flood Damage Analysis (MD-FDA)

The MD-FDA method is a flood damage cost calculating method that uses flood depth and damage cost regression curves. The MD-FDA method considers flood depth data relevant to the land use information such as residential and industrial areas. Using the determinations of damaged items relevant to flood depth and land use data including the spatial distribution of property, damage costs are calculated by multiplication of the inundated inclusion ratio and damaged assets. Damaged assets are divided according to several components such as infrastructure, household contents, farmland, crops, and tangible and inventory assets. These assets can be calculated for each area, and values are multiplied by the probability of damage relevant to flood depth and the inundated inclusion ratio to calculate flood damage costs (Fig. 2).

Determinations of flood damage costs in structures located within residential areas vary with flood depth and structure types. Flood depth is classified into four stages and structures are classified into three types (e.g., detached houses, apartments, and terraced houses) as shown in Table 1. Damage costs for structures can be determined by multiplying the structure price,

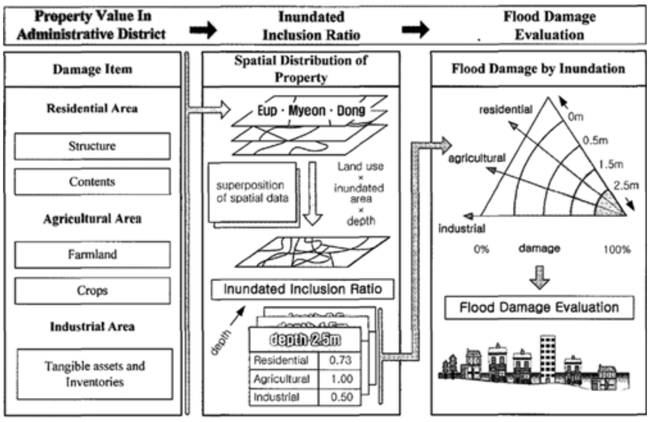

Fig. 2. Procedure for Estimating Flood Damage Costs by MD-FDA

Table 1. Probability of Structure Damage Relevant to the Flood Depth

Probability of damage (%)	Flood depth (m)			
	0–0.5	0.5–1.5	1.5–2.5	>2.5
Detached house	15	40	83	100
Apartment	$15/n_1$	$40/n_1$	$83/n_1$	$100/n_1$
Terraced house	$15/n_2$	$40/n_2$	$83/n_2$	$100/n_2$

(n_1: number of apartment floors, n_2: number of terraced house floors)
(MOLIT, 2004)

Table 2. Probability of Content Damage Relevant to the Flood Depth

Flood depth (m)	0–0.5	0.5–1.0	1.0–2.0	2.0–3.0	>3.0
Probability of damage (%)	14.5	32.6	50.8	92.8	100

(MOLIT, 2004)

Table 3. Probability of Industrial Property Damage Relevant to the Flood Depth

Probability of damage (%)	Flood depth (m)			
	0–0.5	0.5–1.0	1.0–2.0	>2.0
Tangible assets	25	50	80	100
Inventory assets	15	30	60	100

(MOLIT, 2004)

inundated inclusion ratio for structures, and the probability of structural damage relevant to the flood depth (Eq. (1)).

$$\textit{Damage cost of structure} = \textit{structure price} \times \textit{inundated inclusion ratio} \times \textit{probability of structure damage} \tag{1}$$

The damage costs for contents are determined based on the assumption that contents are irrelevant to the types of structures. Probability of content damages relevant to flood depth is classified into five stages as shown in Table 2. Damage costs for contents can be determined by multiplying the content prices, inundated inclusion ratio in residential areas, and probability of content damages relevant to flood depth (Eq. (2)).

$$\textit{Damage cost of contents} = \textit{contents price} \times \textit{inundated inclusion ratio} \times \textit{probability of contestns damage} \tag{2}$$

Table 4. Industrial Classifications and Property Portions in Jeongeup

Class	Tangible assets	Inventory assets
D	0.021806595	0.052032826
E	0.007998205	0.000457528
F	0.051225406	0.094919012
G	0.032881348	0.094919012
H	0.00642042	0.001217463
I	0.054154218	0.006253795
J	0.027301091	0.017930157
K	0.013885958	0.008181836
L	0	0
M	0.000924999	9.4013E-06
N	0.001092028	0.000446168
O	0.010241461	0.001225297

(KOSTAT, 2012)

Determinations of flood damage costs in industrial areas vary with flood depth and industrial classification. Each industrial class has a respective proportion of tangible and inventory assets (KOSTAT, 2012). Probability of asset damages relevant to flood depth and the industrial classifications are shown in Tables 3 and 4, respectively. Damage costs for industrial property can be determined by multiplying property prices, flood assigned rates in industrial areas, and the probability of property damage relevant to flood depth (Eq. (3)).

$$\textit{Damage cost industriial property} = \textit{property price} \times \textit{inundated inclusion ration} \times \textit{probability of property damage} \tag{3}$$

4. Target Area

The Sintaein basin in the city of Jeongeup, Jeonbuk, South Korea, was selected as the target area to apply the new method for the determination of optimal storage facility locations. The city of Jeongeup is 692.78 km^2 in area, which makes it the second largest city in the Jeonbuk province; it has a population of 120,000 and floods regularly. During the 10-year period from 2002 to 2011, the region was inundated six times. Serious

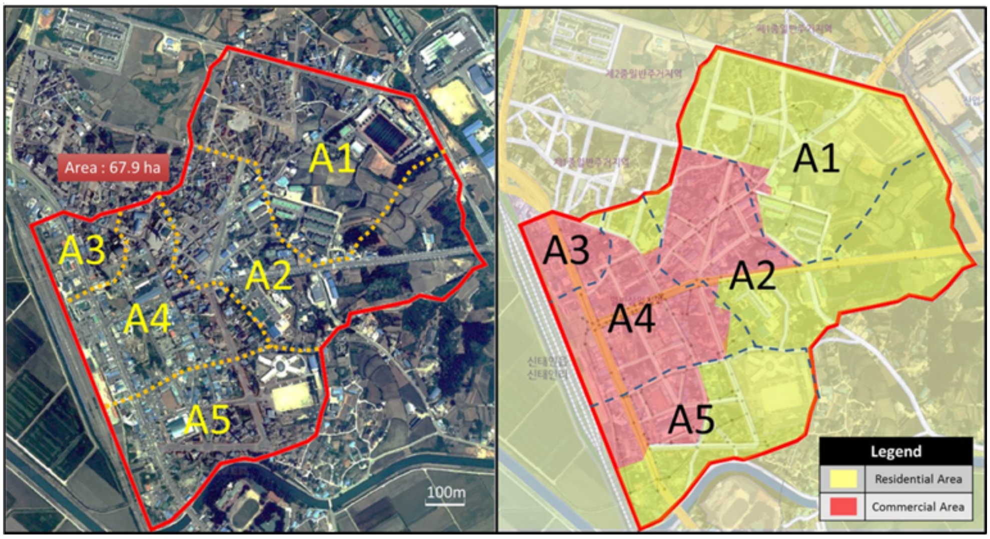

Fig. 3. Sintaein Drainage Area

damage to roads, buildings, and human life occurred, especially in 2011 because of heavy rainfall over 400 mm per day. The region was designated as a flood hazard area in 2012, and 17,200 million wons were allocated for a flood prevention project during 2013 to 2015. This project involved the construction of two rainwater storage sites and improvements to the sewer system. The drainage target area is 67.9 ha and consists of 175 pipe links (Fig. 3).

5. Estimation of the Flood Volume and Damage Cost Relationship

Before estimating the relationship between flood volume and damage costs, a subset of the sub-basins was analyzed to determine regional differences and effects dependent on the storage facility locations. On the basis of the shape of the pipe network system, 2D flood simulations with XP-SWMM software and land use information were conducted within the following five subdivisions: A1, A2, A3, A4, and A5 (Fig. 3, Table 5). A1 is 17.6 ha in area and consists of a residential area including apartments and high schools. A2 is located in the middle of the sewer network, and it is 21.5 ha in area and contains commercial and residential units. A3 is a small commercial area that is 0.7 ha in area. A4 is mainly composed of 15.1 ha of commercial area. A5 is at the bottom of the sewer network, and it is 13.0 ha in area and contains commercial and residential areas. For this area, the flood volume and flood damage costs have already been estimated (Lim *et al.*, 2014). For the current research, eight different 1-hour rainfall events were imposed onto the drainage area, and by using the MD-FDA model and XP-SWMM, which can simulate 2D flood analysis results, the flood volume and flood damage costs were calculated as shown in Table 6. A rainfall scenario was considered to take place over a 1-hour duration and with a uniform time distribution. On the basis of these data, the flood volume and flood damage cost relationship can be derived by fitting the data to regression curves. This relationship has a non-linear form, and the power function of the regression curve was suggested as a key parameter of interest by Lim *et al.* (2014). In A3, the flood damage remained at zero, even though flooding occurred because the flood damage was calculated based on inundation depth. In other words, if overflow occurs, no flood damage will take place until the flood volume reaches a particular point that depends on the basin characteristics and land surface form. Fig. 4 shows a sketch of area A3 and illustrates the relationship between flood depth and damage costs. In this figure, damage costs remain at zero until the flood depth reaches h1.

Table 5. Subdivisions of the Drainage Area

Subarea	Area (ha)	Land use data
A1	17.6	Residential: 96.8% Commercial: 3.2%
A2	21.5	Residential: 66.3% Commercial: 33.7%
A3	0.7	Residential: 4.1% Commercial: 95.9%
A4	15.1	Residential: 13.5% Commercial: 86.5%
A5	13.0	Residential: 68.1% Commercial: 31.9%

To address this issue, a new regression equation was required. Simply adding an x-intercept to the equation solved this problem. The relationship is called the Belehradek power function or simply the shifting power function, and it was used to find the proper equation (Eq. (4)).

$$y = a(x-b)^{c} \tag{4}$$

The results of fitting the data to the regression curve are shown in Fig. 5, and the regression equations are shown in Table 7. In the case of A3, note the different flood volume–damage cost

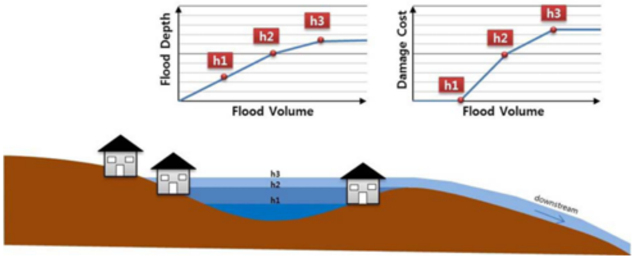

Fig. 4. Flood Volume–damage Cost Relation in the A3 Area

Table 6. Flood Volume–damage Cost Table

Subarea \ Rainfall		80 mm	90 mm	100 mm	110 mm	120 mm	130 mm	140 mm	150 mm
A1	Flood volume (m^3)	11.5	63.9	384.3	1,310.5	2,461.2	4,199.9	5,559.5	9,428.9
	Damage cost (10^3 won)	0	0	15,839	28,144	44,258	45,648	57,981	76,986
A2	Flood volume (m^3)	3.9	3,591.9	5,021.9	6,467.1	7,142.3	8,400.2	12,879.4	15,458.5
	Damage cost (10^3 won)	6,728	19,352	28,704	29,252	30,392	30,815	35,928	46,586
A3	Flood volume (m^3)	200.4	203.3	291.5	341.7	404.3	519.8	500.4	651.9
	Damage cost (10^3 won)	0	0	0	31,988	55,252	55,152	54,988	55,252
A4	Flood volume (m^3)	4,087.6	6,225.9	13,053.8	13,379.4	14,265.8	15,128	16,597.1	19,733.3
	Damage cost (10^3 won)	34,519	76,773	93,971	96,763	97,200	113,104	114,020	117,709
A5	Flood volume (m^3)	1,098.1	1,781.7	2,716.8	2,908.1	2,934.6	3,468	3,735.7	5,937.5
	Damage cost (10^3 won)	15,769	56,392	61,000	63,317	78,000	83,691	94,110	132,000

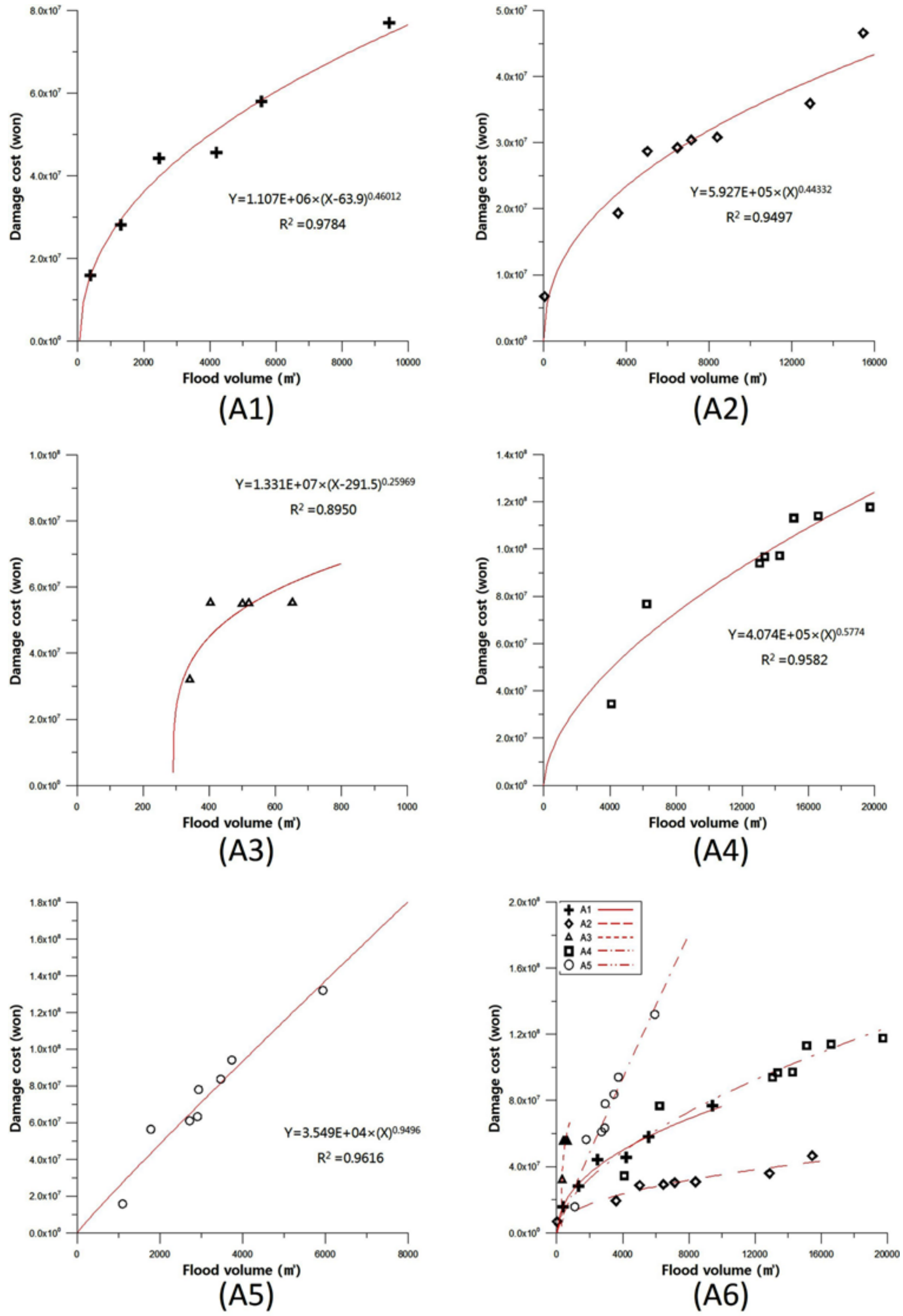

Fig. 5. Regression Analysis of Flood Volume Versus Damage Cost

Table 7. Regression Equations for Flood Volume–damage Cost Curves

Subarea	Flood volume (x[m^3]) – damage cost (y[won]) regression curve
A1	$y = 1.107\text{E} + 06(x\text{-}63.9)^{0.46012}$ ($R^2 = 0.9784$)
A2	$y = 5.927\text{E} + 05(x)^{0.44332}$ ($R^2 = 0.9497$)
A3	$y = 1.331\text{E} + 07(x\text{-}291.5)^{0.25969}$ ($R^2 = 0.8950$)
A4	$y = 4.074\text{E} + 05(x)^{0.5774}$ ($R^2 = 0.9582$)
A5	$y = 3.549\text{E} + 04(x)^{0.9496}$ ($R^2 = 0.9616$)

relation compared to the others. This pattern originated from the surface flow in the 2D flood simulation, and water was transferred from the upstream flooded region (A3) to the downstream flooded region (A4). Fig. 4 shows the characteristics of the A3 subarea as well.

The minimum R^2 was 0.895, and this value was detected in A3; in general, all the regression equations fit well. The results show that A5 was the most impacted area, where there existed high flood damage costs in relation to the flood volume.

Fig. 6. Potential Locations for Storage Facility Construction

6. Determination of Optimal Storage Facility Locations

In order to determine the best locations for rainwater storage sites, 10 potential locations were studied (Fig. 6). The potential sites were evaluated according to standard criteria for selection with regard to the adequacy of having enough space for constructing an underground storage tank for public services. Additionally, up to three storage installations were assessed for the 10 potential locations. The number of combination cases can be calculated simply by using the mathematical expression shown in Eq. (5).

$$nCr = \frac{n!}{(n-r)!r!} \qquad (5)$$

where n is the number of potential locations and r is the number of the storage installation. The number of cases considered for the construction of a single storage facility was 10, two storage facilities was 45, three storage facilities was 120, and the total number of combination cases was 175.

7. Rainfall Scenarios

During this research, rainfall scenarios with different probabilities were applied to analyze the flood reduction effect of various storage options while regions experienced a range of rainstorms with different severities. The following six different return periods of rainfall were selected for analysis: 5-year, 10-year, 30-year, 50-year, 70-year, and 100-year periods. Usually, the critical duration is selected by using the outfall hydrograph to obtain the maximum discharge. However, for this method, the critical duration was selected by considering the storage volume to obtain the maximum volume. Using the SWMM model, a 2-hour rainfall duration in the target area was simulated as the critical amount. However, to closely examine the effects of storage facility performance, 1-hour, 2-hour, and 3-hour rainfall durations were all applied, and this resulted in 18 different rainfall scenarios as shown in Table 8. The probabilistic characteristics of the rainfall data were derived from the Korea Probability Rainfall Information data set (MOLIT, 2011). For the time distribution of rainfall, a Huff 3rd quartile distribution was applied in accordance with the regulations stipulated in the Improvement and Supplement of Probability Rainfall in South Korea (MOLIT, 2011), as shown in Table 9 and Fig. 7.

Table 8. Total Precipitation for Different Rainfall Scenarios

Duration (h)	Return period (year)					
	5	10	30	50	70	100
1	57.7	67.4	82.3	89.1	93.6	98.2
2	75.7	88.3	107.5	116.3	122.2	128.1
3	87.0	101.0	122.2	131.9	138.4	145.0

(MOLIT, 2011)

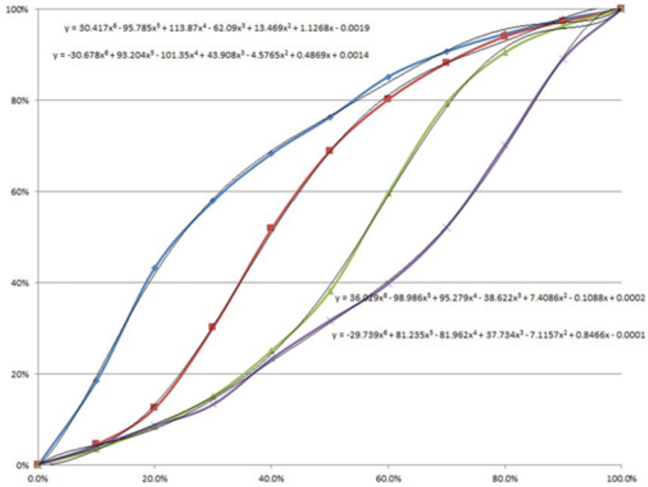

Fig. 7. Regression Equations for Huff Distributions in the City of Jeongeup

Table 9. Huff Distribution Table for the City of Jeongeup

	Cumulative percent of storm time										
	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Huff 1	0.0	18.5	43.3	57.9	68.3	76.3	85.2	90.7	94.6	97.8	100.0
Huff 2	0.0	4.5	12.5	30.2	51.8	68.9	80.2	88.2	94.0	97.3	100.0
Huff 3	0.0	3.5	8.5	15.1	25.1	38.1	59.7	79.4	90.5	96.3	100.0
Huff 4	0.0	4.2	8.6	13.3	23.3	31.7	39.8	52.1	70.2	89.1	100.0

8. Model for Determination of the Optimal Storage Facility Locations

The model simulations were conducted for two different purposes, namely, to select storage facility locations that could minimize the total flood volume in the watershed and to select storage facility locations that could minimize total flood damage costs. The number of possible storage facilities ranged from one to three, and the rainfall-runoff simulations were constructed by SWMM.

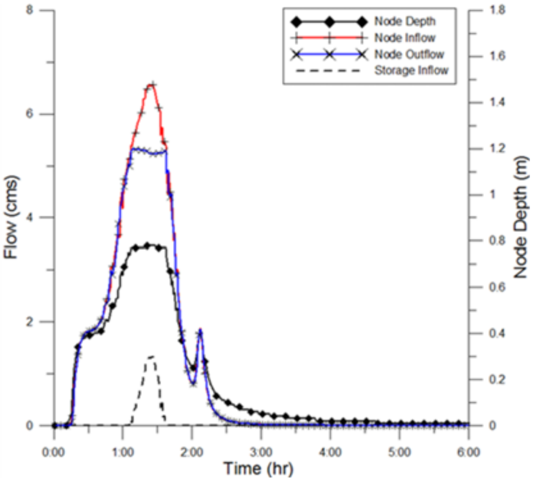

Fig. 8. Results of the Storage Flow Simulation at Potential Location 8

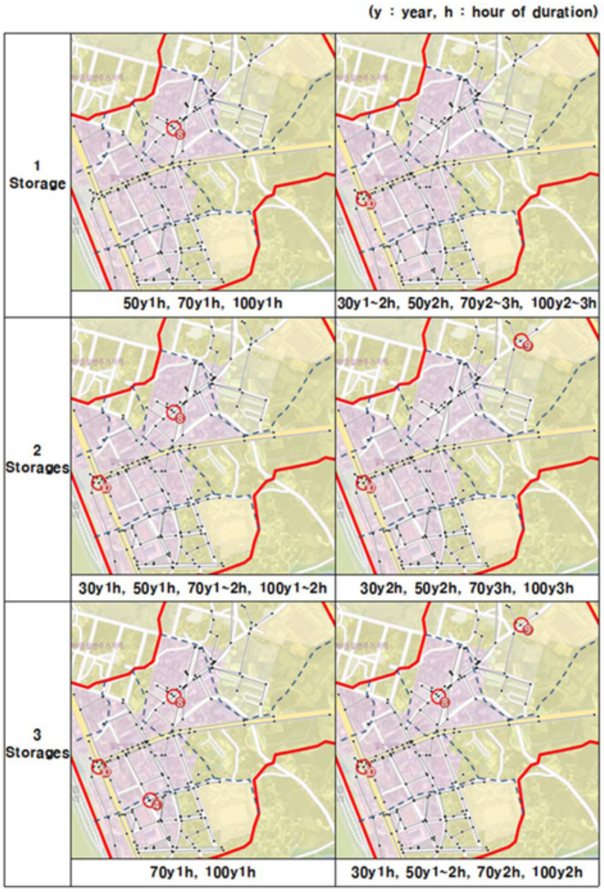

Fig. 9. Storage Facility Locations for Volume Minimization

Table 10. Results for the Volume Minimization Analysis (30-year return period)

Duration (h)	Number of storage facilities	Location ID (required volume (m^3))	Total flood (reduced volume) (m^3)/ reduction rate (%)	Total damage costs (reduced cost) (10^6 won)/ reduction rate (%)	Peak flow (reduced peak flow) (m^3/s) / reduction rate (%)
1 h	0	n / a	7,172 (0) / 0	108.9 (0) / 0	13.63 (0) / 0
	1	10 (3,001)	4,778 (2,393) / 33.4	85.5 (23.4) / 21.5	13.51 (0.12) / 0.9
	2	8 (2,518)	3,060 (4,112) / 57.3	67.8 (41.1) / 37.8	13.48 (0.15) / 1.1
		10 (2,547)			
	3	8 (2,499)	2,306 (4,866) / 67.9	58.4 (50.5) / 46.4	13.49 (0.14) / 1.0
		9 (768)			
		10 (2,537)			
2 h	0	n/a	2,179 (0) / 0	52.4 (0) / 0	12.69 (0) / 0
	1	10 (2,320)	812 (1,367) / 62.7	30.2 (22.2) / 42.3	12.64 (0.05) / 0.4
	2	9 (282)	552 (1,627) / 74.7	25.1 (27.3) / 52.0	12.64 (0.05) / 0.4
		10 (2,280)			
	3	1 (226)	437 (1,742) / 79.9	20.5 (31.9) / 60.8	12.66 (0.03) / 0.2
		9 (282)			
		10 (2,185)			
3 h	0	n / a	36 (0) / 0	2.4 (0) / 0	11.13 (0) / 0
	1	n / a	n / a	n / a	n / a
	2	n / a	n / a	n / a	n / a
		n / a			
	3	n / a	n / a	n / a	n / a
		n / a			
		n / a			

All simulations were conducted by applying codes in Visual Basic 6.0 while using SWMM dll components. Scenarios were created for a total of 18 rainfall events and 175 combinations of storage facility installations. In this study, the complete enumeration method was used for finding the optimal and best locations. Generally, complete enumeration as used in this study was more appropriate to employ than an optimization algorithm.

In this study, the volume of the storage facility was assumed to be infinite, so that all the inflows could be stored in the storage facility and prevented from re-entering conduits or the sewer

Table 11. Results for the Volume Minimization Analysis (50-year return period)

Duration (h)	Number of storage facilities	Location ID (required volume (m^3))	Total flood (reduced volume) (m^3)/ reduction rate (%)	Total damage costs (reduced cost) (10^6 won)/ reduction rate (%)	Peak flow (reduced peak flow) (m^3/s) / reduction rate (%)
1 h	0	n / a	9,814 (0) / 0	131.5 (0) / 0	13.98 (0) / 0
	1	8 (3,272)	6,809 (3,005) / 30.6	111.8 (19.7) / 15	14.01 (-0.02) / -0.2
	2	8 (3,229)	4,620 (5,194) / 52.9	87.5 (44.0) / 33.4	13.82 (0.16) / 1.2
		10 (2,904)			
	3	8 (3,203)	3,729 (6,085) / 62.0	78.8 (52.7) / 40.1	13.82 (0.16) / 1.2
		9 (901)			
		10 (2,897)			
2 h	0	n / a	4,680 (0) / 0	81.1 (0) / 0	12.99 (0) / 0
	1	10 (3,564)	2,012 (2,668) / 57.0	51.2 (29.9) / 36.8	12.80 (0.19) / 1.5
	2	9 (524)	1,495 (3,185) / 68.0	43.7 (37.4) / 46.2	12.80 (0.19) / 1.5
		10 (3,546)			
	3	8 (1,397)	1,008 (3,673) / 78.5	34.2 (46.9) / 57.8	12.86 (0.13) / 1.0
		9 (528)			
		10 (2,847)			
3 h	0	n / a	339 (0) / 0	17.6 (0) / 0	12.32 (0) / 0
	1	9 (73)	264 (75) / 22.1	15.1 (2.4) / 13.8	12.32 (0) / 0
	2	3 (588)	216 (123) / 36.4	12.7 (4.8) / 27.4	12.37 (-0.05) / -0.4
		9 (74)			
	3	3 (370)	214 (125) / 36.8	12.7 (4.9) / 27.9	12.36 (-0.04) / -0.3
		8 (27)			
		9 (74)			

Table 12. Results for the Volume Minimization Analysis (70-year return period)

Duration (h)	Number of storage facilities	Location ID (required volume (m^3))	Total flood (reduced volume) (m^3)/reduction rate (%)	Total damage costs (reduced cost) (10^6 won)/reduction rate (%)	Peak flow (reduced peak flow) (m^3/s)/reduction rate (%)
1 h	0	n / a	11,673 (0) / 0	146.3 (0) / 0	14.12 (0) / 0
	1	8 (3,724)	8,237 (3,435) / 29.4	126.0 (20.3) / 13.8	14.25 (-0.13) / -0.9
	2	8 (3,683)	5,815 (5,857) / 50.2	101.2 (45.1) / 30.8	14.01 (0.11) / 0.8
		10 (3,111)			
	3	4 (1,859)	4,719 (6,954) / 59.6	83.2 (63.1) / 43.1	13.87 (0.25) / 1.8
		8 (3,666)			
		10 (2,714)			
2 h	0	n / a	6,632 (0) / 0	100.5 (0) / 0	13.14 (0) / 0
	1	10 (4,220)	3,265 (3,368) / 50.8	68.2 (32.3) / 32.1	12.98 (0.15) / 1.2
	2	8 (2,115)	2,165 (4,467) / 67.4	51.6 (48.9) / 48.7	12.89 (0.25) / 1.9
		10 (3,452)			
	3	8 (2,080)	1,492 (5,141) / 77.5	43.1 (57.4) / 57.1	12.89 (0.25) / 1.9
		9 (713)			
		10 (3,455)			
3 h	0	n / a	1,502 (0) / 0	43.0 (0) / 0	12.53 (0) / 0
	1	10 (1,458)	611 (891) / 59.3	25.6 (17.4) / 40.6	12.53 (0) / 0
	2	9 (178)	429 (1,073) / 71.4	21.7 (21.4) / 49.6	12.52 (0.01) / 0
		10 (1,436)			
	3	1 (161)	380 (1,122) / 74.7	19.0 (24.0) / 55.8	12.47 (0.06) / 0.5
		9 (178)			
		10 (1,381)			

Table 13. Results for the Volume Minimization Analysis (100-year return period)

Duration (h)	Number of storage facilities	Location ID (required volume (m^3))	Total flood (reduced volume) (m^3)/reduction rate (%)	Total damage costs (reduced cost) (10^6 won)/reduction rate (%)	Peak flow (reduced peak flow) (m^3/s) / reduction rate (%)
1 h	0	n / a	13,623 (0) / 0	160.8 (0) / 0	14.38 (0) / 0
	1	8 (4,102)	9,841 (3,782) / 27.8	140.9 (19.9) / 12.4	14.32 (0.06) / 0.4
	2	8 (4,070)	7,198 (6,425) / 47.2	115.8 (45.0) / 28.0	14.24 (0.14) / 1.0
		10 (3,317)			
	3	4 (2,118)	5,833 (7,789) / 57.2	94.2 (66.6) / 41.4	14.10 (0.28) / 2.0
		8 (4,050)			
		10 (2,931)			
2 h	0	n / a	8,621 (0) / 0	119.2 (0) / 0	13.28 (0) / 0
	1	10 (4,789)	4,672 (3,949) / 45.8	83.8 (35.4) / 29.7	13.14 (0.14) / 1.0
	2	8 (2,802)	3,030 (5,591) / 64.9	64.3 (54.9) / 46.0	13.06 (0.22) / 1.7
		10 (3,972)			
	3	8 (2,754)	2,165 (6,456) / 74.9	54.6 (64.6) / 54.2	13.06 (0.22) / 1.7
		9 (901)			
		10 (3,964)			
3 h	0	n / a	3,012 (0) /0	62.1 (0) / 0	12.70 (0) / 0
	1	10 (3,233)	1,059 (1,953) / 64.9	34.8 (27.3) / 44.0	12.63 (0.07) / 0.5
	2	9 (358)	724 (2,288) / 76.0	29.1 (33.0) / 53.2	12.64 (0.06) / 0.5
		10 (3,191)			
	3	1 (285)	573 (2,439) / 81.0	24.0 (38.2) / 61.4	12.66 (0.04) / 0.3
		9 (363)			
		10 (3,064)			

network. The basic storage facility inlet depth (threshold depth) was calculated by the maximum water depth from a 10-year return period rainfall with a 2-hour duration. When the inlet depth reached the threshold depth, the storage facility inflows operated so that rainwater over the inlet depth was stored in the facility. The flow in the storage simulations is shown in Fig. 8.

9. Minimizing the Total Flood Volume

The results for the potential storage facility locations related to minimizing total flood volume are presented in Tables 10 to 13 and Fig. 9. Fundamentally, the location of the storage facility was dependent on the rainfall intensity. In the cases of 50-, 70-, and 100-year return periods with 1-hour durations, location 8 (A2) was selected. In the case of the 30-year period, location 10 (A4) was selected. These tendencies stemmed from the capacity of the upper conduit. When high intensity rainfall occurred, the conduit could not receive runoff and flood waters from the upper areas inundated downstream areas such as location 8 (A2). Otherwise, when low intensity rainfall occurred, most of the runoff was carried through the conduits. As a result, flooding occurred at certain downstream nodes such as at location 10 (A4) because of the discharge buildup. The highest reduction volume was 3,949 m^3 (45.8%) among the total of 8,621 m^3 in location 10 (A4).

During the installation of two storage facilities, location 8 (A2) and location 10 (A4) were selected in most cases. Area A4 was selected in most cases because this area was easily inundated with large flood volumes as shown in Fig. 5. The highest reduction volume was 6,425 m^3 (47.2%) among the total of 13,623 m^3. During the installation of three storage facilities, location A5 was selected as it had a high rainfall intensity. The highest reduction volume was 7,789 m^3 (57.2%) among the total of 13,623 m^3.

10. Minimizing Damage Costs

The results for the potential storage facility locations related to minimizing flood damage costs are shown in Tables 14 to 17 and Fig. 10. During the installation of a single storage facility, similar areas such as location 10 (A4) were selected. On the other hand, in the case of 100-year rainfall with a 1-hour duration, location 4 (A5), which showed the most sensitive flood volume–damage cost relationship, was selected. The highest damage cost reduction was 35.4 million won (29.7%) among the total of 119.2 million won in location 10 (A4).

During the installation of two storage facilities, locations 4 (A5) and 8 (A2) were deemed suitable options for high intensity rainfall events such as 70- or 100-year rainfall with 1-hour durations. A similar tendency was observed during the installation of a single storage facility. The highest damage cost reduction was 47.3 million won (29.4%) among the total of 113.5 million won. During the installation of three storage facilities, locations 4 (A5), 8 (A2), and 10 (A4) were selected and the highest damage cost reduction was 66.6 million won (41.4%) among the total of 160.8 million won.

According to the results, potential storage facility locations for reducing damage costs were similar to some of those identified for minimizing the flood volume. For example, most cases

Table 14. Results for the Cost Minimization Analysis (30-year return period)

Duration (h)	Number of storage facilities	Location ID (required volume (m^3))	Total flood (reduced volume) (m^3)/reduction rate (%)	Total damage costs (reduced cost) (10^6 won)/reduction rate (%)	Peak flow (reduced peak flow) (m^3/s) / reduction rate (%)
1 h	0	n / a	7,172 (0) / 0	108.9 (0) / 0	13.63 (0) / 0
	1	10 (3,001)	4,778 (2,393) / 33.4	85.5 (23.5) / 21.5	13.51 (0.12) / 0.9
	2	8 (2,518)	3,060 (4,112) / 57.3	67.8 (41.1) / 37.8	13.48 (0.15) / 1.1
		10 (2,547)			
	3	8 (2,499)	2,306 (4,866) / 67.9	58.4 (50.5) / 46.4	13.49 (0.14) / 1.0
		9 (768)			
		10 (2,537)			
2 h	0	n / a	2,179 (0) / 0	52.4 (0) / 0	12.69 (0) / 0
	1	10 (2,320)	812 (1,367) / 62.7	30.2 (22.2) / 42.3	12.64 (0.05) / 0.4
	2	9 (282)	552 (1,627) / 74.7	25.1 (27.3) / 52.0	12.64 (0.05) / 0.4
		10 (2,280)			
	3	1 (226)	437 (1,742) / 79.9	20.5 (31.9) / 60.8	12.66 (0.03) / 0.2
		9 (282)			
		10 (2,185)			
3 h	0	n / a	36 (0) / 0	2.4 (0) / 0	11.13 (0) / 0
	1	n / a	n / a	n / a	
	2	n / a	n / a	n / a	n / a
		n / a			
	3	n / a	n / a	n / a	n / a
		n / a			
		n / a			

Table 15. Results for the Cost Minimization Analysis (50-year return period)

Duration (h)	Number of storage facilities	Location ID (required volume (m^3))	Total flood (reduced volume) (m^3)/reduction rate (%)	Total damage costs (reduced cost) (10^6 won)/reduction rate (%)	Peak flow (reduced peak flow) (m^3/s)/reduction rate (%)
1 h	0	n /a	9,814 (0) / 0	131.5 (0) / 0	13.98 (0) / 0
	1	10 (3,310)	7,096 (2,718) / 27.7	107.4 (24.1) / 18.3	13.82 (0.16) / 1.2
	2	8 (3,229)	4,620 (5,194) / 52.9	87.5 (44.0) / 33.4	13.82 (0.16) / 1.2
		10 (2,904)			
	3	4 (1,612)	3,791 (6,023) / 61.4	73.2 (58.3) / 44.3	13.61 (0.37) / 2.7
		8 (3,199)			
		10 (2,490)			
2 h	0	n /a	4,680 (0) / 0	81.1 (0) / 0	12.99 (0) / 0
	1	10 (3,564)	2,012 (2,668) / 57.0	51.2 (29.9) / 36.8	12.80 (0.19) / 1.5
	2	8 (1,438)	1,499 (3,181) / 68.0	41.4 (39.7) / 49.0	12.85 (0.14) / 1.0
		10 (2,842)			
	3	1 (423)	1,193 (3,487) / 74.5	33.6 (47.6) / 58.6	12.89 (0.09) / 0.7
		8 (1,427)			
		10 (2,745)			
3 h	0	n /a	339 (0) / 0	17.6 (0) / 0	12.32 (0) / 0
	1	3 (595)	289 (50) / 14.9	15.1 (2.5) / 14.2	12.37 (-0.05) / -0.4
	2	3 (588)	216 (123) / 36.4	12.7 (4.8) / 27.4	12.37 (-0.05) / -0.4
		9 (74)			
	3	3 (370)	214 (125) / 36.8	12.7 (4.9) / 27.9	12.36 (-0.04) / -0.3
		8 (27)			
		9 (74)			

included location 10 (A4) because it is located at a downstream area where flood discharges buildup causing a large amount of flood volume, and it also has large sensitivity in terms of the flood damage costs. However, there were significant differences between these two methods such as at location 4 (A5). When considering a single storage facility, the location changed from 8 (A2) to 4 (A5) for 100-year rainfall with a 1-hour duration. In this case, the total flood volume increased by 1,627 m^3 from 9,841 m^3 to 11,468 m^3. However, the flood damage costs decreased by 6.5 million won from 140.9 million won to 134.4 million

Table 16. Results for the Cost Minimization Analysis (70-year return period)

Duration (h)	Number of storage facilities	Location ID (required volume (m^3))	Total flood (reduced volume) (m^3)/reduction rate (%)	Total damage costs (reduced cost) (10^6 won)/reduction rate (%)	Peak flow (reduced peak flow) (m^3/s)/reduction rate (%)
1 h	0	n / a	11,673 (0) / 0	146.3 (0) / 0	14.12 (0) / 0
	1	10 (3,503)	8,760 (2,913) / 25.0	121.9 (24.4) / 16.7	14.01 (0.11) / 0.8
	2	4 (2,117)	6,387 (5,286) / 45.3	101.2 (45.1) / 30.8	14.08 (0.05) / 0.3
		8 (3,717)			
	3	4 (1,859)	4,719 (6,954) / 59.6	83.2 (63.1) / 43.1	13.87 (0.25) / 1.8
		8 (3,666)			
		10 (2,714)			
2 h	0	n / a	6,632 (0) / 0	100.5 (0) / 0	13.14 (0) / 0
	1	10 (4,220)	3,265 (3,368) / 50.8	68.2 (32.3) / 32.1	12.98 (0.15) / 1.2
	2	8 (2,115)	2,165 (4,467) / 67.4	51.6 (48.9) / 48.7	12.89 (0.25) / 1.9
		10 (3,452)			
	3	1 (571)	1,685 (4,948) / 74.6	41.8 (58.7) / 58.4	12.92 (0.22) / 1.7
		8 (2,111)			
		10 (3,379)			
3 h	0	n / a	1,502 (0) / 0	43.0 (0) / 0	12.53 (0) / 0
	1	10 (1,458)	611 (891) / 59.3	25.6 (17.4) / 40.6	12.53 (0) / 0
	2	9 (178)	429 (1,073) / 71.4	21.7 (21.4) / 49.6	12.52 (0.01) / 0
		10 (1,436)			
	3	1 (161)	380 (1,122) / 74.7	19.0 (24.0) / 55.8	12.47 (0.06) / 0.5
		9 (178)			
		10 (1,381)			

Table 17. Results for the Cost Minimization Analysis (100-year return period)

Duration (h)	Number of storage facilities	Location ID (required volume (m^3))	Total flood (reduced volume) (m^3)/reduction rate (%)	Total damage costs (reduced cost) (10^6 won)/reduction rate (%)	Peak flow (reduced peak flow) (m^3/s)/reduction rate (%)
1 h	0	n / a	13,623 (0) / 0	160.8 (0) / 0	14.38 (0) / 0
	1	4 (2,386)	11,468 (2,155) / 15.8	134.4 (26.4) / 16.4	14.21 (0.17) / 1.2
	2	4 (2,366)	7,754 (5,869) / 43.1	113.5 (47.3) / 29.4	14.21 (0.17) / 1.2
		8 (4,095)			
	3	4 (2,118)	5,833 (7,789) / 57.2	94.2 (66.6) / 41.4	14.10 (0.28) / 2.0
		8 (4,050)			
		10 (2,931)			
2 h	0	n / a	8,621 (0) / 0	119.2 (0) / 0	13.28 (0) / 0
	1	10 (4,789)	4,672 (3,949) / 45.8	83.8 (35.4) / 29.7	13.14 (0.14) / 1.0
	2	8 (2,802)	3,030 (5,591) / 64.9	64.3 (54.9) / 46.0	13.06 (0.22) / 1.7
		10 (3,972)			
	3	1 (725)	2,383 (6,238) / 72.4	53.3 (65.9) / 55.3	13.06 (0.22) / 1.7
		8 (2,797)			
		10 (3,912)			
3 h	0	n / a	3,012 (0) /0	62.1 (0) / 0	12.70 (0) / 0
	1	10 (3,233)	1,059 (1,953) / 64.9	34.8 (27.3) / 44.0	12.63 (0.07) / 0.5
	2	9 (358)	724 (2,288) / 76.0	29.1 (33.0) / 53.2	12.64 (0.06) / 0.5
		10 (3,191)			
	3	1 (285)	573 (2,439) / 81.0	24.0 (38.2) / 61.4	12.66 (0.04) / 0.3
		9 (363)			
		10 (3,064)			

won. When considering two storage facilities, the locations changed from 8 (A2) and 10 (A4) to 4 (A5) and 8(A2), respectively, for the same scenarios. Similarly, the total flood volume increased by 556 m^3 from 7,198 m^3 to 7,754 m^3, whereas the flood damage costs decreased by 2.3 million won. This is significant proof that the flood volume–damage cost relation can be used effectively when considering optimal locations for storage facilities to minimize flood damage costs.

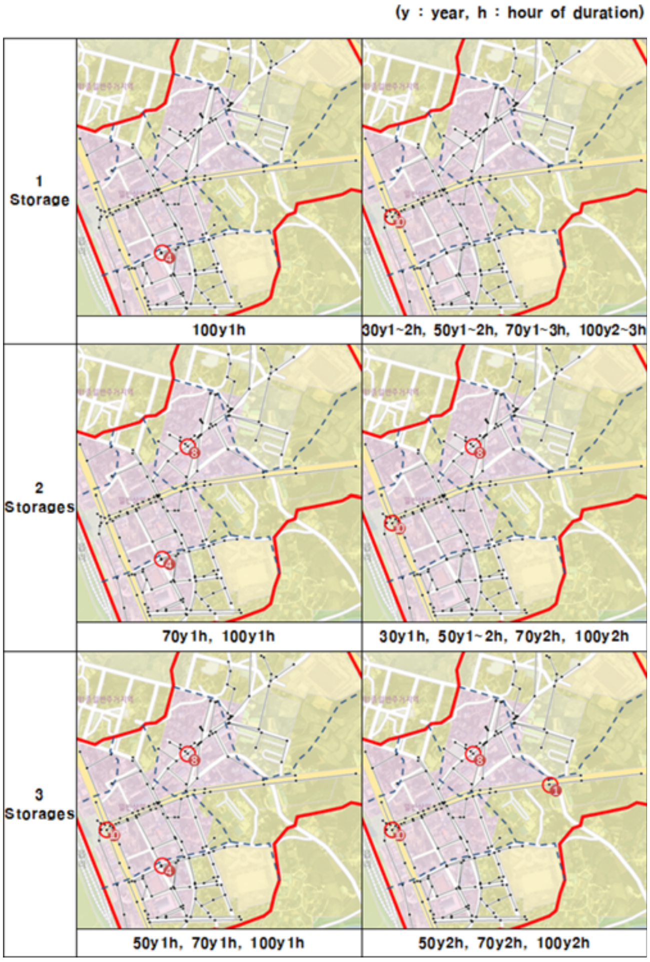

Fig. 10. Storage Facility Locations for Cost Minimization

11. Conclusions

Determinations of appropriate locations for rainwater storage sites are critical in urban areas that are prone to flooding. In particular, the performance of a storage facility can vary greatly depending on its location. In previous studies that identified optimal storage locations, the main focus was on reductions in flood volume, whereas here, actual damage costs caused by the flooding were considered. Specifically, in this research, a new method was proposed to identify optimal rainwater storage locations based on the flood damage costs that were assessed by using regional flood volume and damage cost relationships. The approach was tested in the Sintaein River basin of South Korea by using the Multi-Dimensional Flood Damage Analysis (MD-FDA) method and 2D flood simulations; a regional flood volume–damage cost relationship was calculated first. This relationship was used to reflect the characteristics of each subdivision area including important features and expected property damages. By utilizing regression equations, determinations of optimal storage facility locations for minimizing flood damage costs were made, and comparisons were also made to the results from the conventional method for minimizing flood volumes. While implementing the proposed method, the total flood volume was higher than that achieved under the conventional method; however, the flood damage costs were successfully reduced with the proposed method. In conclusion, the proposed method for determining optimal storage site locations based on flood damage costs should be a valuable new tool for flood prevention efforts in urban areas.

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