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Evaluation of multi-use stormwater detention basins for improved urban watershed management

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Abstract:

Detention basins are used to capture postdevelopment runoff and control the peak discharge of the outflow using orifices and weirs. The use of detention basins is typical practice in the construction of new developments on the fringe of existing urban areas, such as the Ulsan–Hwabong district in the city of Ulsan, South Korea. In this study, the required volume and flooding area of a detention basin was determined to control development outflow peaks for 2-year, 10-year, and 100-year design storms with type II rainfall distributions as characterized by the US Department of Agriculture's Soil Conservation Service method. The rainfall–runoff simulation model used was the US Environmental Protection Agency's Storm Water Management Model (EPA-SWMM) 5, which is the latest version of the software, updated for Windows. We designed three cases of detention basins multi-staged by 2-year, 10-year, and 100-year design storms and verified the designs with the application of 49 years (1961–2009) of hourly historical rainfall data. The three detention basin designs were compared in terms of the total construction and land costs as well as the benefits associated with recreational facilities or parking lot use. As a result, the design sizes of the detention basins are slightly greater than the actual sizes needed based on the historical rainfall application. Multi-use detention basins (MDBs) based on 2-year and 10-year design storms were found to yield 37.4% and 22.8% benefits, respectively, for recreational facility use compared with detention basins without multi-use space, and the results also indicate that benefits accrue after 6.5 years for parking lot use. The results of this study suggest that an MDB based on a 2-year design storm is the most cost-effective design among the three cases considered for Ulsan, South Korea. Copyright © 2012 John Wiley & Sons, Ltd.

KEY WORDS multi-use detention basin; SCS type II rainfall distribution; EPA-SWMM 5; recreational facility; parking lot

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INTRODUCTION

Urbanization causes complications in natural stormwater runoff patterns. The main purpose of urban stormwater management is to mitigate hydrological and environmental urban development impact by such means as attenuating peak discharges and pollutant loads. Flooding in particular has been recognized as an important issue very early on because it has a direct effect on human activity, and flooding attenuation techniques have been investigated and developed. Best management practices (BMPs) involve the use of well-known types of facilities to reduce urban flooding and nonpoint source pollutants. The standard practice of BMP is to require that the peak flow after development does not exceed the predevelopment peak flow for specified design storms. Detention basins have been more widely used than other BMPs because they are the most traditional, and their concepts are simple to apply. However, these BMPs are only used during the wet weather season; they do not operate during the dry weather season. Multi-use detention basins (MDB) have a more positive impact on residential property values than 'single-use' detention basins (SDB) (Lee and Li, 2009). For this reason, municipalities in many countries recommend developing floodplain or detention basin areas for multi-use during dry weather. Many recreational facilities, public parking lots, and agricultural farms are located in floodplain or detention basin areas. Usually, these can be placed on parcels of land with relatively low marginal land use values, thus effectively reducing the total installation cost. This is particularly beneficial in dense urban areas where land can be very expensive.

Several studies have demonstrated various aspects of the economic benefits of detention basins. Moglen and McCuen (1990) suggested an economic framework to design detention basins based on flood and sediment control. They estimated the flood control benefit of detention basin construction compared with the estimated flood damage cost and used a simple trap efficiency equation for the estimation of sediment control. They found that sediment control benefits were minimal in comparison to flood control benefits and that regional detention facilities provide greater water quality benefits than on-site detention control. Cutter *et al.* (2008) investigated the cost-effectiveness of BMPs, including detention basin implementation in Los Angeles with

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centralized and decentralized BMPs. They adopted the spreadsheet-based storage, treatment, overflow, and runoff model (SS STORM) developed by Lee *et al.* (2005) to compute BMP volume and showed that a decentralized incentive-based approach for the use of BMPs in areas with low land use values is likely to be more cost-effective than a centralized approach. Lee and Li (2009) investigated the influence of MDBs and SDBs on residential property values. They employed a hedonic price model, in the form of a multiple linear regression model, to predict home values as a function of housing structure attributes, spatial and location features, and neighbourhood environmental attributes (including detention basin–related variables) and applied the model to communities in College Station, TX. MDBs were shown to have a significant positive impact on residential property values, while SDBs had a negative impact.

In South Korea, researchers have recently focused on the evaluation of floodplains for the prevention of flooding, as well as their environmental and ecological characteristics, and tried to quantify these nonmarket valuations. Kwak *et al.* (2010) evaluated the flood control performance and ecological benefits of a constructed washland. They employed the US Army Corps of Engineers Hydrologic Engineering Center's River Analysis System (HEC-RAS) to analyse the effects of flood control and investigated the ecological effects on habitats and species. Yoo *et al.* (2010) studied the economic benefit of constructed washlands by estimating benefits such as flooding, water quality control, and ecological effectiveness. They applied the choice experiment (CE) method, a nonmarket valuation technique based on a questionnaire survey, to quantify various functions and services in a constructed washland. The same concepts can be applied to the construction of an MDB area. However, these studies only addressed the economic benefits of detention basins associated with reducing flooding and capturing waterborne pollutants downstream (Moglen and McCuen, 1990; Cutter *et al.*, 2008; Yoo *et al.*, 2010) or those associated with ecological effects (Kwak *et al.*, 2010). The benefits of MDBs in particular have not been investigated or quantified; in fact, their benefits, such as the possibility that an MDB may become a feature attraction or that it may improve a property's appeal (US EPA, 2004), have only been considered in the abstract.

In South Korea, many rainfall distribution methods, such as the Huff distribution method, the Yen and Chow method, and the Mononobe distribution method, have been applied to the design of storm sewer systems and other hydro-infrastructure (KICT, 2000). However, the US Soil Conservation Service (SCS) design rainfall distribution method has not been employed in South Korea. This is because the SCS method predicts greater flooding than the Huff method, which is the best-known rainfall distribution method in South Korea. However, the SCS distribution method is well suited for application to temporally concentrated rainfall events or intense rainfall events of short duration, which makes the SCS method well suited for application to South Korea. Furthermore, the multi-stage detention basin design method has not yet been introduced in South Korea (Seong and Han, 2001) even though it is well suited for the design of detention basins in preventing flooding. For these reasons, the applicability of the SCS design rainfall distribution method and the multi-stage detention basin design method for the validation of hydro-infrastructure design in South Korea should be investigated.

The main objective of the current study was to quantify the economic benefit of an MDB containing a floodplain area for multi-use, compared with a conventional detention basin, by market valuation, including the construction cost and land cost. Floodplain areas for MDBs are designed in accordance with different floodplain flood frequencies. This study investigated MDB benefits based on recreational and parking lot applications. This study did not consider flood damage benefits and only investigated land use area change. In addition, this study applied a multi-stage detention basin design based on the SCS rainfall distribution method, which is widely used in the USA, to a target watershed in Ulsan, South Korea.

The Ulsan–Hwabong apartment district in Ulsan, South Korea, was adopted as the experimental watershed, and the US Environmental Protection Agency's Storm Water Management Model, EPA–SWMM 5 (Rossman, 2005), which is an updated version of SWMM (Huber and Dickinson, 1992) with an advanced graphical user interface, was used to simulate the watershed runoff and develop the detention basin designs. SWMM 5 was selected because it simulates the behaviour of stormwater sewer systems and detention basins well. The detention basin designs were verified by means of a long-term simulation using 49 years (1961–2009) of hourly historical rainfall data. The main focus of the study was on comparing the costs and benefits of MDBs versus SDBs, taking into consideration both construction costs and land costs in the Ulsan–Hwabong district of Ulsan, South Korea. A soccer field and a playground were considered for recreational features, and a parking lot was considered for cost savings.

APPLICATION

Watershed

The Ulsan–Hwabong district in Ulsan, South Korea, built by the Korea Land Corporation (1990) was selected as the research site for this study. This district was developed with separate sewer systems for residential, commercial, and public areas. The total area of this watershed is 1 064 246 m^2, and its storm sewer system discharges into the Taehwa River. The Ulsan–Hwabong district was divided into ten subwatersheds for analysis with the EPA-SWMM 5 model, and one of the ten was selected for this study. The drainage area of the selected subwatershed is 109 700 m^2 and is composed of 25 junctions and 24 conduits, as shown in Figure 1. All junction elevations and conduit slopes were taken from Park and Jang (2005).

Figures 2a and 2b are schematic illustrations of the predevelopment and postdevelopment storm sewer drainage, respectively, for the selected subwatershed in the EPA-SWMM 5 model. It is assumed that the current condition, as shown in Figure 1, was postdevelopment. The predevelopment condition is typically a simple system composed of a few conduits and junctions with small areas of impervious surfaces and a high average infiltration rate. Imperviousness ratios of 5% and 60% were adopted in this study for predevelopment and postdevelopment, respectively. In both Figures 2a and 2b, points represent sewer junctions, straight lines represent sewer pipes, and curved lines represent the gutter system. In EPA-SWMM 5, surcharged water is out of the system if water is surcharged at the junction. For this reason, it is necessary to introduce the gutter system to keep the surcharged water for the mass balance. Black squares represent subwatersheds. Dynamic wave routing was selected to represent actual flow conditions. This selection accounts for backwater effects, pressurized flow, and looped or parallel sewers in a storm sewer system (Rossman, 2005). The Horton equation, which is the default model, was selected for infiltration simulation. In Figure 2b, a storage mark represents a detention basin. Two orifices and one weir can be added to a detention basin to make a three-stage detention basin. Details of the detention basin designs for the three different design storms considered are shown in Figures 4 and 5, and additional details are explained in the Section on Designs of Detention Basins.

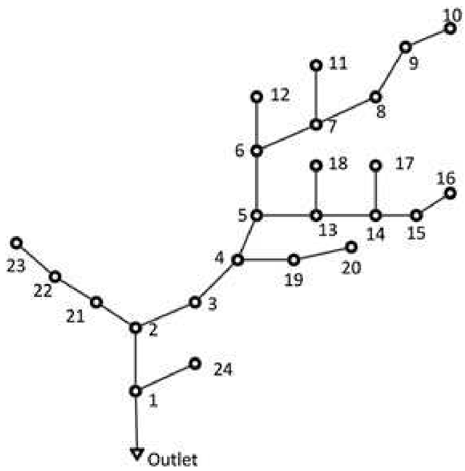


Figure 1. Schematic of the existing sewer system (postdevelopment) of the Ulsan–Hwabong subwatershed (Park and Jang, 2005)

Design rainfall distributions

The SCS rainfall distribution method, which is used extensively for detention basin design with EPA-SWMM 5 throughout the USA (Nehrke and Roesner, 2004; Brown *et al.*, 2009), was used in this study. For a given design, rainfall depths depending on frequency and duration in Ulsan were obtained from KICT (2000). The US Department of Agriculture's Soil Conservation Service developed four synthetic 24-hr rainfall distributions (SCS types I, IA, II, and III) for different geographical regions of the USA (Kent, 1973). The SCS type II rainfall distribution was selected for the design storms considered in this study because it is applicable to a larger portion of the area of the USA (Akan and Houghtalen, 2003; Brown *et al.*, 2009) than the other types. The total rainfall volume and the distribution of the rainfall for SCS type II are provided in Figure 3. The rainfall distribution is provided at 15-min intervals for a variety of return periods. Six different

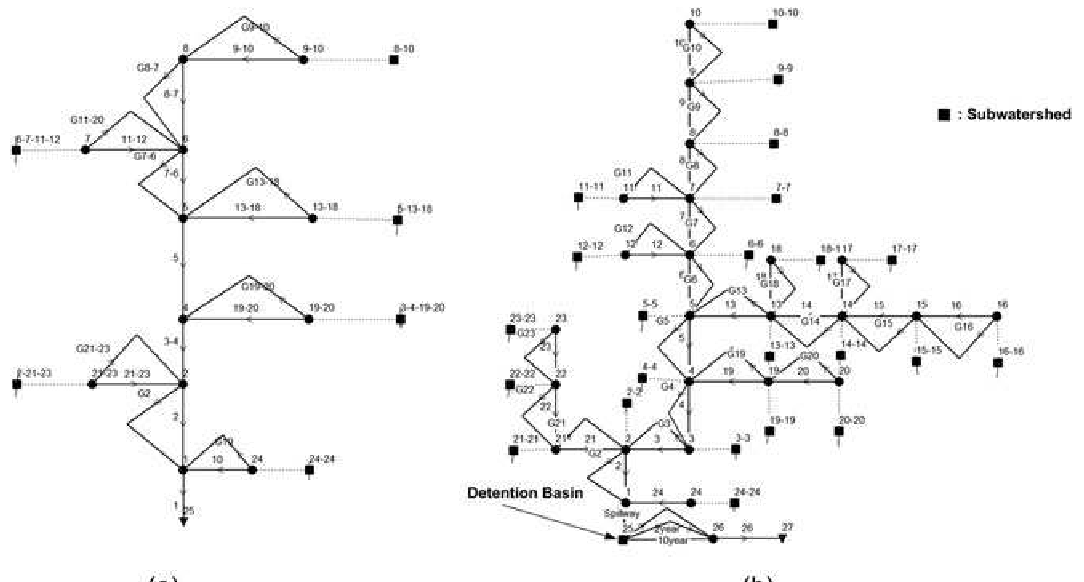


Figure 2. Schematic diagram modelling the Ulsan–Hwabong subwatershed in SWMM 5: (a) predevelopment; (b) postdevelopment plus a detention basin

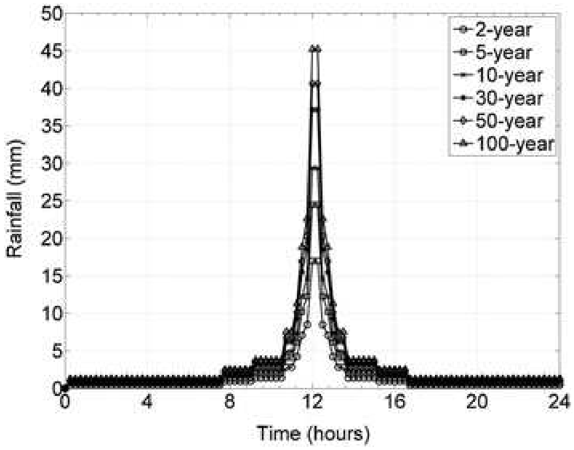


Figure 3. SCS type II hyetographs of 2- to 100-year return periods in Ulsan

design rainfall distributions, namely, 2-year, 5-year, 10-year, 30-year, 50-year, and 100-year design storms, were adopted in this study to assess the detention basin designs.

Designs of detention basins

Three different detention basin designs, shown in Figure 4, were investigated. These basins were modelled at the outlet of the subwatershed and designed for multi-stage control based on 2-year, 10-year, and 100-year design storms; the different shapes for Cases 2 and 3 allowed different MDBs to be tested. The flooding frequencies were selected to encompass the typical range of flooding frequencies for small urban catchments (UDFCD, 2004). Case 1, the SDB, does not have multi-use land space, as shown in Figure 4a. Case 2, an MDB (Figure 4b), has multi-use space for the 10-year design storm, and Case 3, also considered an MDB (Figure 4c), has multi-use space for the 2-year design storm, based on Nehrke and Roesner (2004). A 2-year design storm is defined as the design storm with the shortest return period in this study because 2-year storm events are often considered small storms by drainage and flood control engineers (Guo and Urbonas, 1996). The suggested side slopes for the SDB and the MDB were 1/4 and 1/50, respectively (Schueler, 1987; Urbonas and Stahre, 1993; WEF and ASCE, 1998; Brown *et al*., 2009). Each detention basin has two orifices to control the discharge of the 2-year and 10-year design storms and one weir to control a 100-year design storm (Nehrke and Roesner, 2004). In other words, the surface areas of the detention basins are different because of the different flood frequency criteria for the floodplains, even though the total volumes are almost the same, as shown in Figure 5.

RESULTS AND DISCUSSION

Peak flow attenuation

Figure 6 illustrates the water depths associated with the three detention basin designs for the six design rainfall distributions. Water depths in the detention basins for the 2-, 10-, and 100-year design storms matched the stage depths in the detention basins well. In addition, as Figure 7 shows, storm discharge through the designed detention basins for postdevelopment matches the discharge for the predevelopment condition in Case 1.

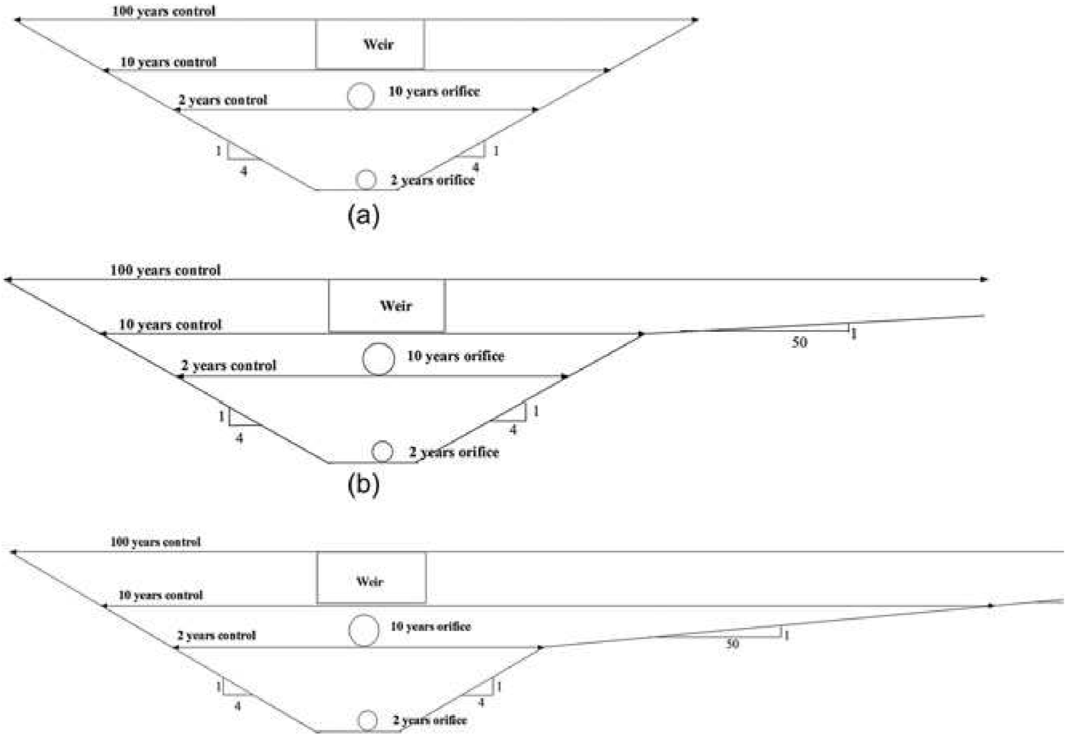
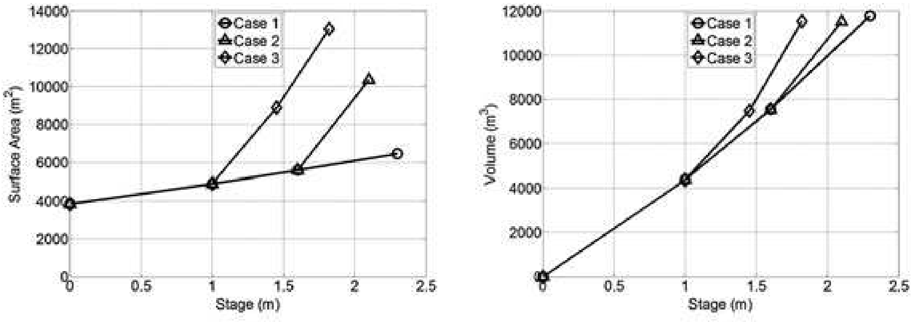
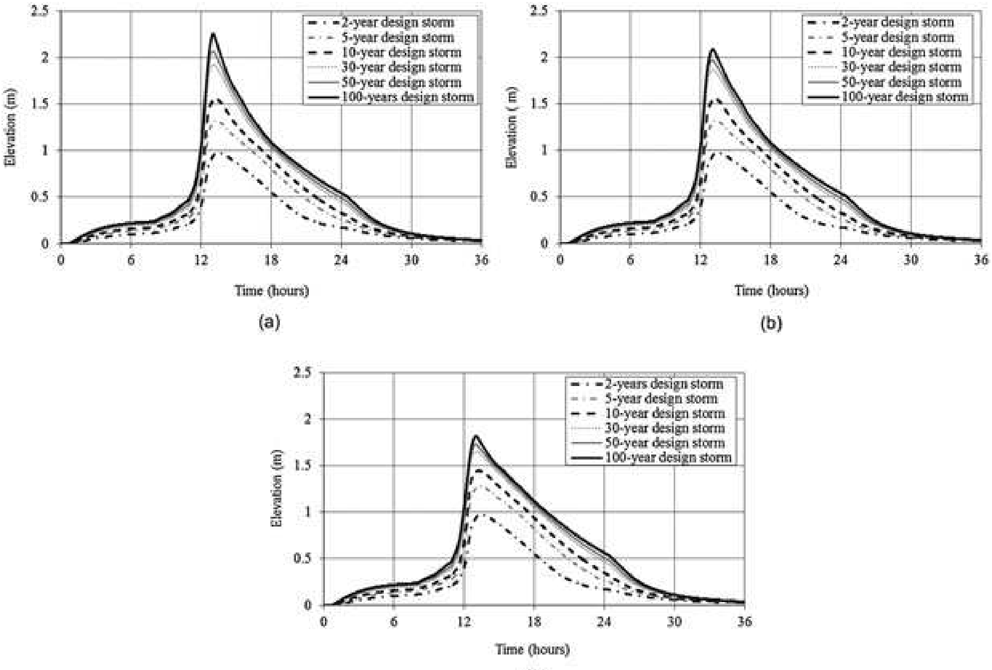


Figure 4. Three detention basin designs



(a) (b)

Figure 5. Geometric features of three detention basins: (a) stage–surface area curve; (b) stage–volume curve



(a) (b) (c)

Figure 6. Water depth changes based on design storms in three detention basins: (a) Case 1; (b) Case 2; (c) Case 3

The 5-, 20-, 30-, and 50-year design rainfall distributions were found to be automatically matched with discharges for the predevelopment condition in, for example, Case 1. It is presumed that an MDB can also control other adjacent design storms with return periods shorter than 100 years at discharge levels matching predevelopment conditions. All three detention basin designs are suitable for lowering peak flows to the predevelopment stage. All three detention basin designs are also effective at performing peak attenuation through size and location adjustments to the orifices and weirs.

Verification of detention basin design using historical rainfall data

Figure 8 shows the water depths in the three detention basins based on historical rainfall data (1961–2009) obtained from the Korea Meteorological Administration (http://web.kma.go.kr/eng/index.jsp). Table I provides estimates of exceedance depth days and exceedance per year based on the depth criteria for flooding and flood warnings related to the multi-use space in the three cases from Figure 8. The total depths are 2.3 m, 2.1 m, and 1.8 m for Cases 1, 2, and 3, respectively, and the depths for multi-use are 1.6 m and 1.0 m for Cases 2 and 3, respectively. Over the 49 years simulated, flooding does not occur at all for Case 1, but occurs on 2 days for Case 2 and 19 days for Case 3, as shown in Table I. These occurrences correspond to values of exceedance per year of 0, 0.04, and 0.38 for Cases 1, 2, and 3, respectively. For practical purposes, flood warning conditions for evacuating a floodplain were considered in the analysis. A flood warning depth of 70% of the flood occurrence depth was assumed for the multi-use space. Thus, the applied flood warning depths for Case 2 and Case 3 were 1.1 m and 0.7 m, respectively. The total numbers of flood warning days over the 49 years were 12 and 57, and the values of exceedance per year were 0.24 and 1.16, for

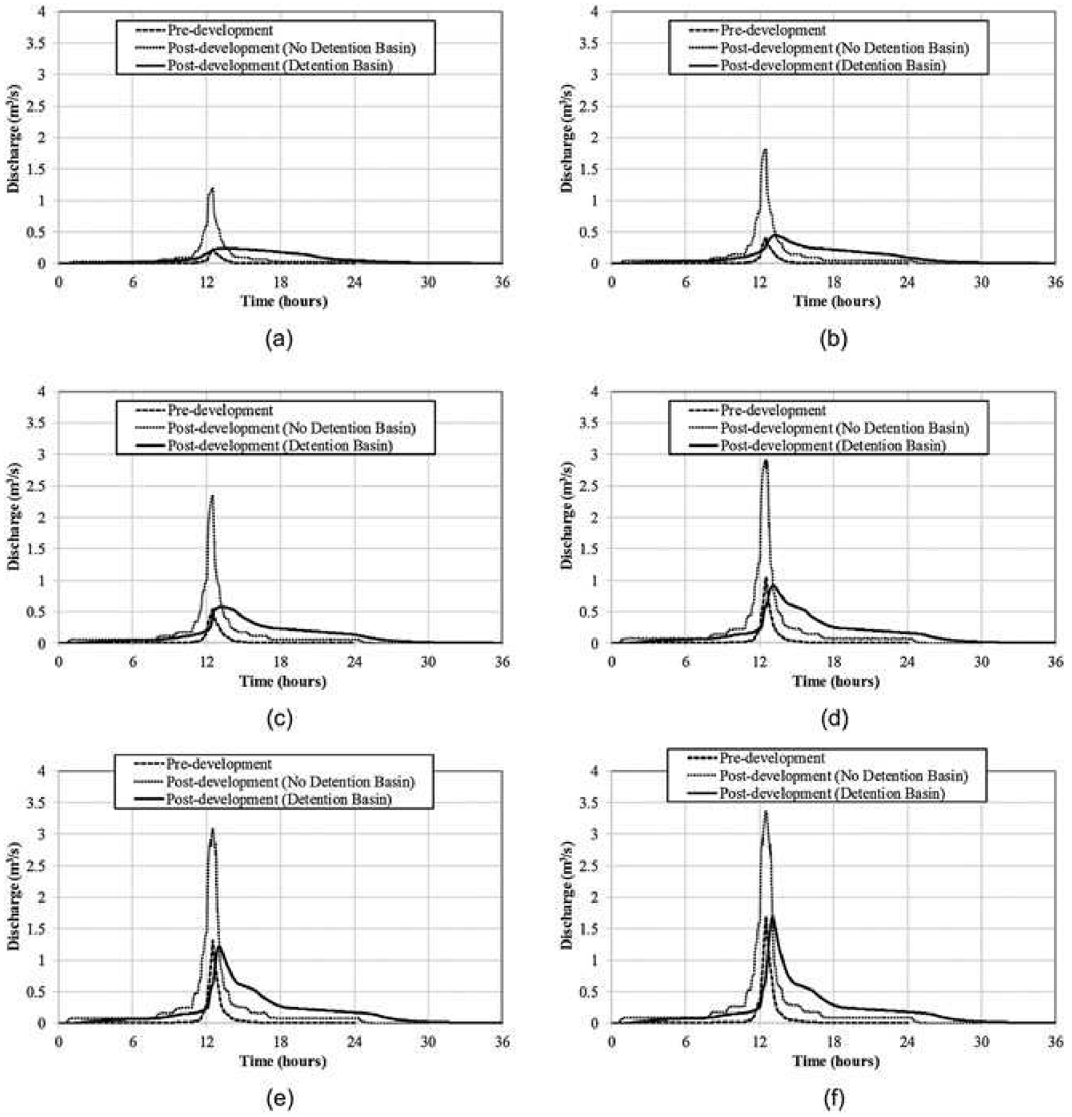


Figure 7. Hydrographs for peak flow attenuation depending on design storms for Case 1: (a) 2-year design storm; (b) 5-year design storm; (c) 10-year design storm; (d) 30-year design storm; (e) 50-year design storm; (f) 100-year design storm

Case 2 and Case 3, respectively. This indicates a likelihood of flooding of 0.24 days and 1.16 days per year for Cases 2 and 3, respectively. These occurrence rates are sufficiently small that flooding days need not be considered in the economic assessment of recreational or parking lot use.

Construction cost of MDBs

Figure 9 shows the detention basin volumes, surface areas, and percentages of the subwatershed area used by the three basin designs according to the design storm analysis. This figure shows that the total volume of the three detention basins are the same despite their different shapes, but their surface areas are different to accommodate different multiple uses. Only the 2-year design storm has the same surface area for all three designs. In the case of the 100-year design, Case 1 has a surface area equivalent to 5.9% of the subwatershed, Case 2 has a surface area equivalent to 9.4% of the subwatershed, and Case 3 has a surface area equivalent to 11.9% of the subwatershed. The surface area of Case 3 is twice that of Case 1, allowing multi-use with more land area. The land area is directly related to the construction cost.

Figure 10 shows the estimates of the detention basin construction costs for the three design cases. The rate of monetary exchange used in this study was simply 1 US dollar to 1000 Korean won. Construction costs include excavation, grass mat supply, and land cost estimates, as shown in Table II. The excavation and grass mat costs were estimated to be \$1.2/m^3 and \$7.5/m^2, based on information from the Construction Association of Korea (2005), and the land cost was estimated to be \$54/m^2, based on information from the Korean Officially Assessed Referenced Land Price (OARLP) (2006), assuming that the detention basins were constructed in the residential district at approximately the same time. The land cost was chosen to be the cheapest around the selected subwatershed.

The Case 1 detention basin cannot be multi-use because of its steep side slopes. However, Case 1 has the lowest construction cost. In Case 2, the multi-use space is available above the 10-year design storm stage.

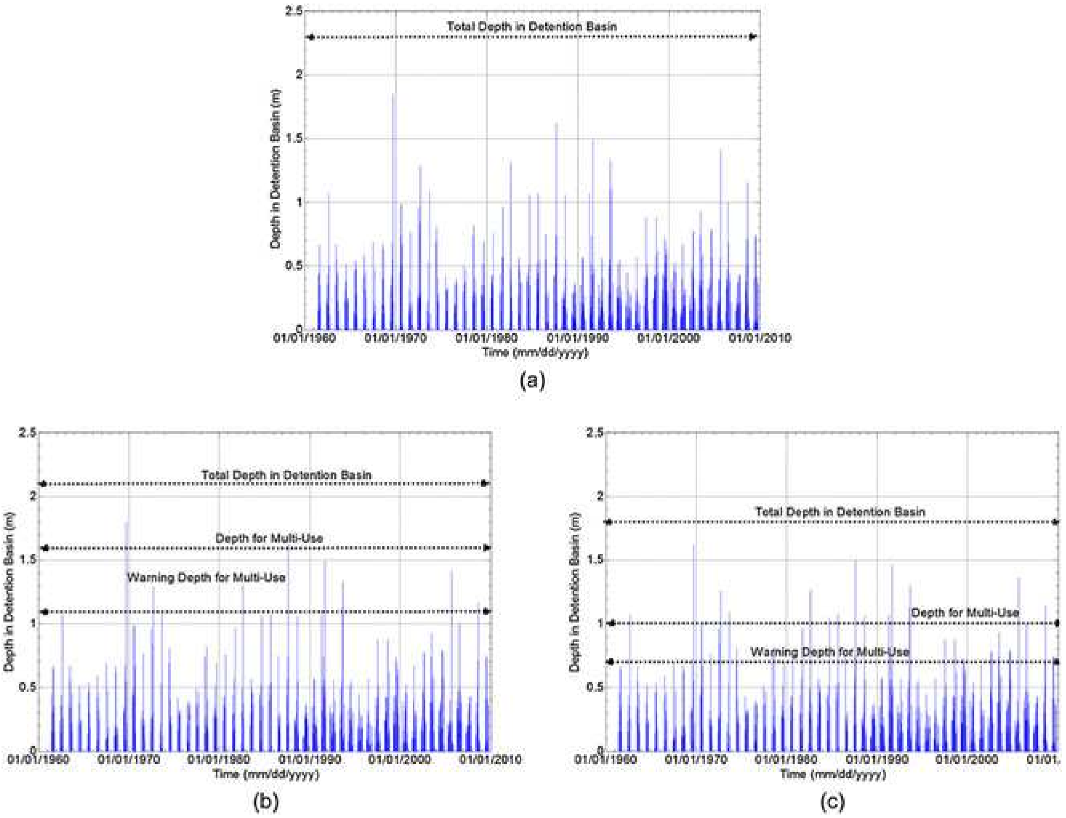


Figure 8. Depths in detention basins based on historical rainfall (1961–2009): (a) Case 1; (b) Case 2; (c) Case 3

Table I. Flooding related to the multi-use space based on historical rainfall data and multi-use space reliability (1969–2009)

Type		Case 1	Case 2	Case 3
Flood occurrence in multi-use space	Total days	0	2	19
	Exceedance per year	0	0.04	0.38
Flood warnings in multi-use space	Total days	0	12	57
	Exceedance per year	0	0.24	1.16

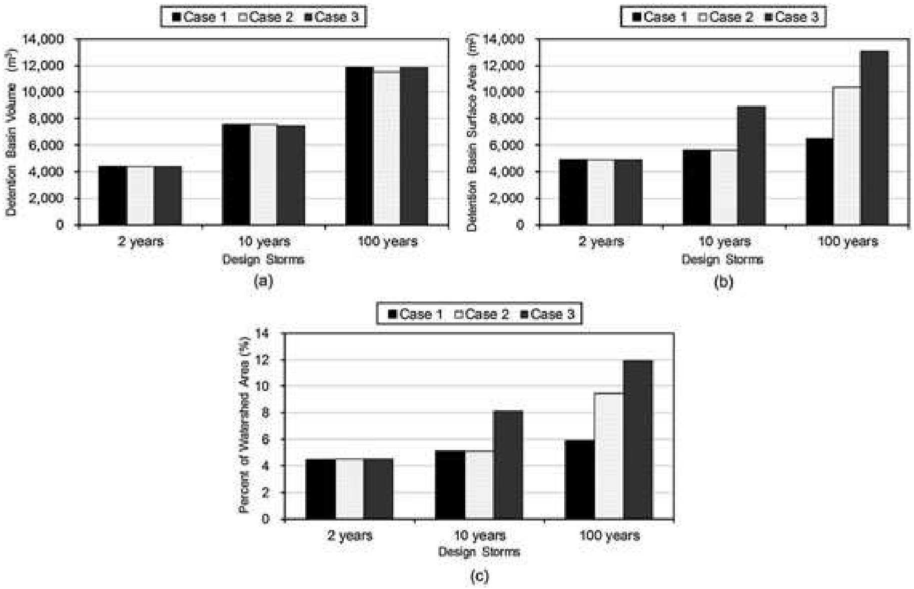


Figure 9. Comparison of basin variables associated with different design storms: (a) detention basin volume; (b) detention basin surface area; (c) percentage of the watershed area

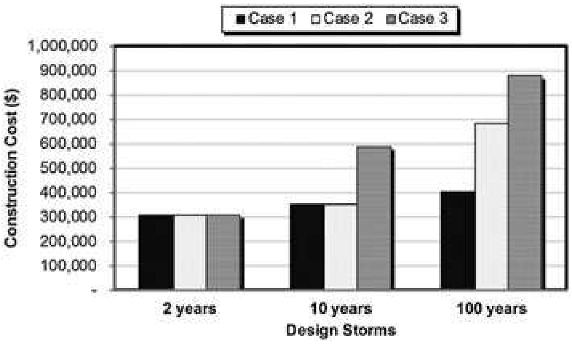


Figure 10. Detention basin construction costs for each case and for different design storms

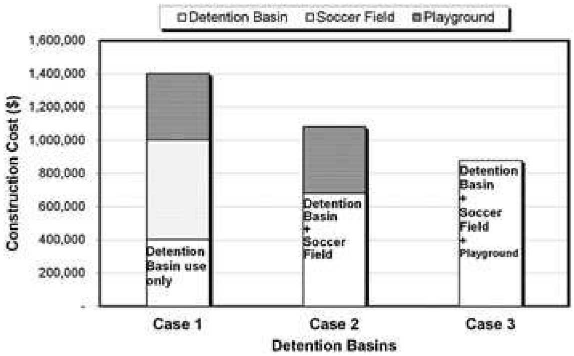


Figure 11. Construction costs of the detention basin with recreation alternatives for three cases

Table II. Unit costs used to estimate the total construction cost

Consideration	Unit cost (US$)
Land cost (m^2) (Officially Assessed Referenced Land Price (OARLP), 2006)	54
Excavation (m^3) (Construction Association of Korea, 2005)	1.2
Grass mat (m^2) (Construction Association of Korea, 2005)	7.5

The construction cost of Case 2 is 70% greater than that of Case 1, but approximately 4500 m^2 of land becomes available for multi-use. The Case 3 detention basin is designed to allow for multi-use space above the 2-year design storm stage. The construction cost of Case 3 is 119% greater than that of Case 1, but approximately 7700 m^2 of land becomes available for multi-use.

Construction costs for detention basins with recreational spaces

This research did not include the nonmarket valuation benefits of MDBs, such as the opportunity for leisure activities and health improvements, but rather focused only on construction costs. It is assumed that recreational facilities are constructed in this watershed: one soccer field and one playground. Soccer field construction costs were estimated to be $600 000 per 6272 m^2 (98 m × 64 m) (Ulsan Metropolitan City Junggu Office, 2006), and playground construction costs were estimated to be $400 000 per 2000 m^2, based on information obtained from the Busan metropolitan city construction headquarters (2003), because suitable estimates were not available for Ulsan, and Busan is one of the closest cities to Ulsan.

Figure 11 shows the total construction costs of the detention basins including the recreational facilities, such as a soccer field and a playground. These total construction costs take into account that if Case 1 is chosen, additional land outside the detention basin will need to be set aside for the construction of both a soccer field and a playground. Thus, the total cost of Case 1 includes additional costs, beyond those of the detention facility, for both a soccer field and a playground. Because Case 2 has multi-use space and less land surface available (90 m × 50 m area), only a playground will accrue additional land costs. In the case of the third detention basin design (Case 3), enough multi-use space is available to contain both a soccer field and a playground, and no extra land is needed for recreational facilities. Thus, the total costs for the detention basin and recreational facilities for the three cases are as follows: Case 1, $1.4 million; Case 2, $1.08 million; and Case 3, $880 000. The cost reduction percentages for Case 2 and Case 3 relative to Case 1 are 22.8% and 37.4%, respectively. These results indicate that MDB may result in lower overall construction costs for stormwater detention facilities when recreation costs are considered in the total cost.

Construction costs for detention basins with parking lot spaces

Monthly parking lot fees and unit parking lot spaces are estimated as shown in Table III. A land cost of $54/$m^2$ and a parking lot fee of $15 per spot per month (Ulsan Metropolitan City Namgu Office, 2008) were assumed in this study. As Table III shows, Case 2 and Case 3 in the floodplain area can create 243 and 416 parking spaces, respectively. Finally, simple cost savings achieved by using parking lots in the floodplain are shown in Figure 12. As this figure shows, Case 2 and Case 3 can be more beneficial than Case 1 after 6.5 years of operation, although the initial construction costs for Case 2 and Case 3 are $280 000 and $480 000 higher, respectively, than the initial construction costs for Case 1. It is assumed that all parking spaces are occupied every day. In addition, the cost savings are greater than the construction costs approximately 12 years and 16 years later for Case 2 and Case 3, respectively.

Table III. Unit values considered for use as a parking lot

Consideration	Unit value
Parking lot fee per month (Ulsan Metropolitan City Namgu Office, 2008)	$15 per spot
Parking lot space per vehicle (Korea MLTM, 2009)	18.5 m^2

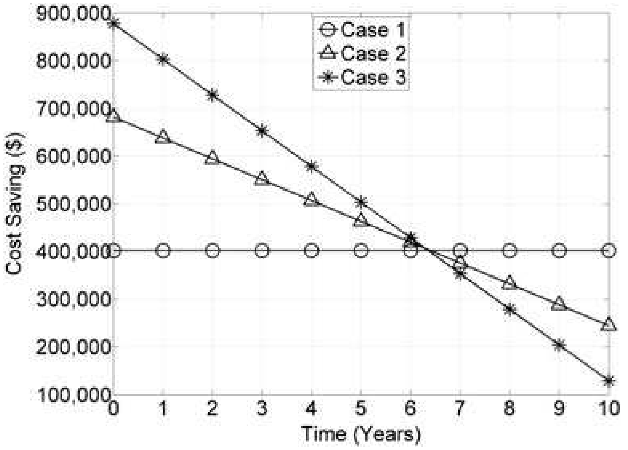


Figure 12. Cost savings due to parking lot fees for three cases

CONCLUSIONS

This study investigated three different detention basin designs located at the outlet of a developing watershed. The economic performance of detention basin designs based on the SCS type II design storm with recreational facility or parking lot use was evaluated. All three designs provide multi-stage control of 2-year, 10-year, and 100-year design storms, but the different shapes of the basins for Cases 2 and 3 allow multi-use in floodplain areas. All three detention basin designs are equivalent in their ability to attenuate flood peaks. They all control peak flow at the predevelopment stage, and 5-, 20-, 30-, and 50-year rainfalls are automatically controlled by meeting the 100-year storm criterion. The three detention basin designs were verified by simulation using hourly historical rainfall data for the period 1961–2009. The results of the analysis showed that the detention basins for the three cases using an SCS type II rainfall distribution are slightly overdesigned in terms of exceedance per year for historical rainfall data. This indicates that the SCS type II rainfall distribution can be applied to South Korea even though the Huff rainfall distribution has been widely used in the country.

This study investigated two types of multi-use in floodplain areas, recreational use and parking lot use, and verified their economic benefit. The detention basin in Case 1 was an SDB and was not designed for multi-use. In Case 2, the multi-use space is available above the 10-year design storm stage because it was designed with two stage controls. In Case 3, the multi-use space is available above the 2-year stage because it was designed for three stage controls. An economic analysis using construction costs showed that Cases 2 and 3 are more beneficial than Case 1, with cost reductions of 22.8% and 37.4%, respectively, even though willingness to pay for recreational use was not included. For the parking lot application, Cases 2 and 3 were found to become more beneficial than Case 1 6.5 years after construction. As a result, Case 3 is the most desirable of the three detention basin designs for Ulsan because of its multi-use potential and economic favourability. In addition, if environmental engineering concerns such as water quality capture volume are taken into consideration, detention basin storage below the 2-year stage can be used to capture nonpoint source pollutants. Therefore, this study suggests that an MDB is suitable for any storm in Ulsan, South Korea, that exceeds a 2-year design storm.

This study demonstrates that a nonmarket valuation of recreational use or parking use in a floodplain can increase the value of an MDB. In future research, the willingness of residents to pay for MDB evaluations should be considered, because residents who pay high costs of living are more willing to pay for recreation or ecological protection than residents who pay low costs of living. Therefore, MDBs are more likely to be cost-effective in cities with high population densities, which usually have higher costs of living.

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