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Impact of BMP Allocation on Discharge and Avoided Costs in an Urbanized Watershed

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최적관리기법 위치분배에 의한 유역단위 하천유량과 회피비용 변화에 관한 연구

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국문요약

본 연구의 목적은 빗물저류 및 흡수 등 우수관리를 위해 설치하는 최적관리기법(Best Management Practices: BMPs)의 효율적인 위치 및 분배 정도를 유역단위에서 살펴보는 것이다. 이를 위해 여러 개의 지류유역과 본류유역으로 이루어진 하나의 대유역을 구축한 후 Hydrological Simulation Program Fortran(HSPF)을 이용하여 도시유역 내 다양한 규모와 위치의 BMPs 시나리오를 제작/모의하였다. 이때 대유역 내 전체 BMPs 면적은 일정하도록 하였으며, 유역하구의 첨두유량과 이와 관련된 회피비용을 효율성의 지표로 활용하였다. 모의 결과 BMPs가 상류지류 유역들에 분산 입지했을 때 가장 높은 효율을 보였으며, 본류유역을 포함하여 소유역 한 곳에 집중되었을 때 가장 낮은 효율을 보였다. 하지만 본 연구는 BMPs의 위치 및 분배 변수를 제외한 BMPs 설계 및 유지관리, 유역 내 다양한 토양특성 등의 기타변수가 통제된 가상유역을 대상으로 진행되었다는 한계를 안고 있다. 따라서 본 연구는 유역관리에서 BMPs 위치 및 분배가 유역관리에 중요한 정책변수일 수 있다는 가능성을 제시하는 데 그치고 있으며, 이러한 가능성은 향후 국내유역에 대한 실증적 모의연구를 통해 논의될 수 있을 것이다.

주제어 분배, 회피비용, 스케일, 유역, 위치, 최적관리기법

Abstract

Urbanized environments are constructed to estimate peak flow and cost savings in response to possible BMP allocation at a watershed scale. The main goal is to explore the proper allocation of sub-watershed level BMPs for peak flow attenuation at a watershed scale. Since several individual site scale BMPs work as a form of aggregated BMPs at a sub-watershed scale, it is a question as to how to properly allocate the sub-watershed level BMPs at a watershed scale. The Hydrological

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Simulation Program-FORTRAN (HSPF) is set up for a hypothetically urbanized watershed. A peak flow is determined to be the primary variable of interest and targeted to characterize the spatial distribution of aggregated BMPs. Construction cost of a regional pond forms the basis of the economic valuation. The results indicate that when total size of BMPs is constant in the entire watershed, (1) it is most effective to have aggregated BMPs in some upper sub-watersheds while the BMPs in either the mainstem sub-watershed or a single sub-watershed are the least effective choices for peak flow attenuation at a watershed scale; (2) savings exist between allocation differences and reduced peak flow increases cost savings. The largest saving is found in the strategy of aggregated BMPs in some upper sub-watersheds. These findings, however, call for follow-up site specific case studies revisiting the watershed scale impacts of BMP allocation. Then, it will be argued that location and extent of decentralization are considerable policy variables for an alternative stormwater management policy at a watershed scale.

❙ Keywords ❙ Allocation, Avoided Cost, BMPs, Hydrology, Scale, Watershed

Ⅰ. Introduction

In response to increasing imperviousness, many municipalities have used Best Management Practices (BMPs) as a hydrological Low Impact Development (LID) technique. BMPs include grassed swales, vegetated green roof covers, permeable pavements, and rain gardens. They are intended to mimic the pre-development site hydrology by their ability to store, infiltrate, evaporate, and detain runoff. Impervious surface coverage is a quantifiable land cover indicator that relates BMPs to stormwater reduction. The area of impervious surface in a watershed is a forcing variable in many hydrologic models, and it has been proposed as a policy variable surrogate for stormwater management (Roesner et al., 2001; Stephenson et al., 1998; Thurston et al., 2003).

Strategically, BMPs can be implemented using a centralized or decentralized approach. A centralized approach utilizes a small number of regional management facilities, such as large regional retention ponds. A decentralized approach means using a large number of small retention ponds, swales, or other infiltration devices distributed throughout the watershed. Historically, local governments have adopted the centralized approach. However, the decentralized approach is gaining more attention recently due to the findings that the technique has better hydrologic functionalities than a centralized approach has in most local practices (Stephenson et al., 1998). Although these findings might suggest broad implementation at site scales, little is known at this point about allocation decisions for BMPs at a watershed scale. Since several individual site scale BMPs work as a form of aggregated BMPs at a sub-watershed scale, it is apparent that the issue is how to properly allocate and implement BMPs at a watershed scale. In this study, BMP allocation scenarios are generated by the conceptual model of flows and interactions which are made up of location, size, and infiltration related parameters associated with BMPs.

In addition to hydrological issues, sound stormwater management requires feasible economic benefit and policy analyses. While considerable interest exists for assessing the hydrologic impacts of BMPs, there are few examples of either analyzing the economic benefits generated from BMPs or related policy implications for municipalities. Although economic benefit assessment is a feasible alternative, it generally has not been explored in the context of the spatial distribution of BMPs. Generally, policy decisions tend to be made primarily based on the sound application of whatever level of scientific understanding exists. Considering the economic context helps implement scientifically valid findings. Possibly, government incentive or regulatory policies for stormwater management could be reasonably established from economic benefit assessments for land development alternatives. The main goal of this experiment is to explore the proper allocation of sub-watershed level BMPs for peak flow attenuation at a watershed scale. This paper presents (1) a hydrologically effective and economically beneficial BMP allocation strategy at a watershed scale and (2) an alternative stormwater management policy reflecting the identified strategy. This paper consists of nine parts: (1) introduction, (2) literature, (3) experimental methods, (4) model setup, (5) experiments, (6) results, (7) policy implication, (8) discussion, and (9) summary and conclusion.

Ⅱ. Literature

As a unit of analysis, development type has emerged as an important focal point for addressing a wide range of social, cultural, and environmental concerns (Bradford and Gharabaghi, 2004; Prince George's County, 1993). Within a development type, BMPs are increasingly being used to reduce off-site runoff and ensure adequate water quality. In these techniques, infiltration capability plays an important role. So far, much research has already been done and compiled for these individual BMPs (Coffman, 2000; CWP, 1998; Prince George's County, 1993; USDOT, 1996; USEPA, 2002a; USEPA, 2000a; USEPA, 2000b).

Valuing the economic benefits or costs from the environment is important in determining any policy change associated there with. If a wetland protects adjacent properties from flooding, the flood protection benefits may be estimated by the damages avoided or by the expenditures property owners make to protect their properties from flooding. "Avoided cost" will be the dollar amount not spent on stream peak flow reduction because the peak flow reduction is being managed by the better BMP allocation strategy. The Avoided cost method assumes that the net costs of strategies are reasonably captured. Although it might be difficult to accurately capture the net costs - the overall costs of BMPs including design, implementation, life cycle cost, operation, and maintenance costs over time - the avoided cost method is frequently used for air/water quality, and other environmental or engineering type studies (Braden and Johnston, 2004; Hanley and Spash, 1994). Therefore, avoided cost would be a feasible approach to differentiate the economic benefits associated with the spatial distribution alternative of BMPs.

Engineering cost methods are appropriate to addressing the spatial distribution alternatives of BMPs because (1) it has been tested in previous work (Heaney et al., 2002; Sample et al., 2003) in linking hydrologic modeling to cost estimation through a process-oriented approach, (2) the economic benefits of the alternatives can be estimated based on existing standard unit costs and functional forms even in the absence of either a study or policy site, and (3) it may be possible to address the benefits in both short and long-term life cycles. Many studies have used engineering cost methods mainly to estimate construction costs of stormwater management facilities. The costs were estimated by using single or combined methods, including functional forms, estimated standard unit costs, social cost estimating methods, and simple/complete hydraulic models in a perspective of short/long term life cycles (Han et al., 1980; Heaney et al., 2002; Moss and Jankiewicz, 1982; Paterson et al., 1993; Sample et al., 2003; Stahre and Urbonas, 1993). Also, in previous works (Braden and Johnston, 2004; Johnston et al., 2006), significant exogenous economic benefits associated with implementation of BMPs were identified. Although the authors systemically investigated BMPs in an economic term, there was no discussion of spatial distribution decisions. It was assumed that all new developments in a watershed would be developed using conservation practices incorporating BMPs, such as wetlands, detention/retention ponds, grassed swales, and forested stream buffers. Authors estimated the size of a 100 year floodplain and calculated the market values of properties in the floodplain. For flood damage estimation, a flood damage formula-based approach was adopted. For infrastructure benefit estimation, differences in culvert costs between scenarios were estimated based on Federal Highway Department design specifications.

Ⅲ. Experimental Methods

1. Theoretical Watershed for a Policy Site

To develop BMP allocation scenarios, a hypothetical watershed is established for a policy site. A hypothetical site creates advantages for the control of variables and the dissemination of generalizable information due to the absence of specific site characteristics. To be useful, information is not necessarily site specific. Specific and timely information is practically better because it can be readily applied. In addition, a generic study tends to narrow and limit various research methods. For example, contingent valuation or hedonic price methods cannot be used unless there is a real policy site. However, a solution for a specific site will be good for that site only in the contemporary socio-economic, geographical, and environmental situations. However, it is necessary to include and capture realistic factors such as hydrologic behaviors, monetary terms and policy an issues for the illustration of better generic information and the development of analysis framework although there is not a policy site.

The hydrologic performance of BMPs will be the focus of analysis in this experiment. Other attributes or values attached to BMPs will not be discussed. These include aesthetics, nonpoint source pollution, water quality, habitat, real estate, and other ecological aspects. The infiltration characteristic of urban grass is assumed to be the representative function of BMPs in this study. Thus, the primary hydrologic processes of BMPs will be infiltration reduction resulting from surface perviousness and roughness. Other hydrologic processes are controlled to minimize variance and uncertainty including evapotranspiration, interception, and recharge.

BMP allocation strategy can be specified as BMP location and extent of decentralization on a watershed scale. The application of sub-watershed scale BMPs is expressed by controlling aggregated hydrologic model parameters at a sub-watershed scale. Accordingly, it is not feasible to identify the specific number and location of individual BMPs in this experiment. As a flood control system, a single regional detention pond at the watershed outlet will be used as an economic benefit indicator from cost saving occurring from the spatial distribution variances. Storage volume is a strong indicator of stormwater pond costs (CWP, 1997).

2. HSPF Modeling

For stormwater analysis, the Hydrological Simulation Program-FORTRAN (HSPF) is adopted to characterize the spatial distribution of BMPs. HSPF has been widely used for the analysis of BMPs in agricultural watersheds (Bicknell et al., 1985; Donigian et al., 1991; Duru et al., 1999; Moore et al., 1992). Bicknell et al. (1985)

modeled hydrology and water quality for the effect of conservation tillage plus contouring for one of the BMPs in the agricultural Iowa River basin, Iowa, US. They demonstrated that HSPF has the capability to simulate hydrology, sediment, and chemical fate/transport in a large river basin with varying meteorological conditions, soils, and agricultural practices. The performance of HSPF was reevaluated in simulating sediment yield from a Claypan agricultural watershed in Central Missouri, US (Duru et al., 1999). Detailed calibrations for the HSPF model were tested to see the impacts of BMPs by Moore et al. (1992). The authors analyzed the effects of not only individual BMPs but also combined BMPs.

In terms of model structure, HSPF has three application modules, including Pervious Land Segment (PERLND), Impervious Land Segment (IMPLND), and Free-Flowing Reach or Mixed Reservoir (RCHRES). As PERLND simulates the water quality and quantity processes that occur on pervious land areas, it is the most frequently used part of HSPF. PERLND simulates the movement of water along three paths - overland flow, interflow, and groundwater flow. Each path experiences differences in time delay and differences in the interactions between water and its various dissolved constituents. IMPLND is used in urban areas where little or no infiltration occurs. RCHRES is used for the simulation of flow hydraulics, sediment, and other water quality constituent behaviors. HSPF employs the Kinematic wave method and the interaction of hydraulic processes to simulate both overland flow and channel flow routing.

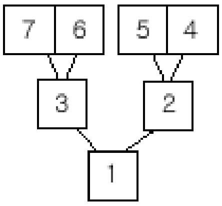
Ⅳ. Model Setup

1. Designing a Watershed for Simulations

The major input data for HSPF modeling are precipitation, watershed geomorphology, land use, and other model parameters. In order to estimate regional detention pond costs, storage volumes should be available as input data. For storage volume sizes, it is required that inflow hydrograph, peak inflow rate, allowable peak outflow rate, time base of the inflow hydrograph, and time peak of the inflow hydrograph.

The stream hierarchy is designed to form three orders: up, middle, and down streams with the most common dendritic drainage pattern. In sizing the watershed, a sub-watershed and a set of sub-watersheds are intended to represent a local municipality and a regional government size watershed encompassing several local municipalities, respectively. A single sub-watershed is sized to 4,047 ha (10,000 ac). A set of seven 4,047 ha (10,000 ac) watersheds is developed in a watershed scale (Fig. 1).

Figure 1 A set of seven 4,047 ha (10,000 ac) watersheds. The number in the watershed indicates reach identification numbers.



The watershed and channel slopes are determined to 0.001. The watershed soil type is ignored in designing a watershed, but it is controlled by infiltration characteristics through HSPF model parameters for individual land use types. For the development of channel length, Hack's equation explaining the relation of channel length and watershed size is referenced. The equation is as follows: A = 0.57 x L1.67, where A is the drainage in square miles and L is the channel length in miles.

Watershed and channel lengths are designed to 16 km (10 mi) and 12 km (7.28 mi), respectively. Manning's N (0.05) is determined by the assumption that the watershed has natural winding stream channels with weeds and pools. The channels are assumed to be a one-dimensional free flow trapezoidal channel. Channel dimensions are determined as functions of drainage area because drainage area is closely correlated with channel width, depth, and cross-sectional area (Dunne and Leopold, 1978). The watershed characteristics are represented by HSPF parameters. The watershed hydrology is affected by numerous parameters, including interflow and infiltration parameters in PERLND and flow routing in the RCHRES. In this study, the infiltration functionality of BMPs is the variable of interest among several variables. Unspecified infiltration and channel characteristics are referenced from the Blackberry Creek watershed study in Illinois, US by Kang and Ahn (2006) because that study has successful calibration results - monthly R2 ranging from 0.7 to 0.9 - for the overall amount of water balance and storm sequence. Located on the western edge of the Chicago Metropolitan area (the third in the US in population) in Kane and Kendall Counties, Illinois, US, the Blackberry Creek watershed is under development pressure from the Chicago region. The Blackberry Creek watershed drains 186.5 km2 as a sub-watershed of the Fox River watershed. Its topography is generally gentle or flat with a minimum elevation of 186.5 m and a maximum elevation of 214.9 m above sea level.

2. Controlled Land Uses and Meteorologic Conditions

Two simplified land use types - BMPs and development - are placed over the watershed. Land use classification is simplified because the differences between urban land use types are not an issue of this study. Urban grass is considered a BMP land use type and its infiltration functionality is used in this model. The development land use type is a lumped urban land use, including residential, commercial, and industrial land uses. It is assumed that the development land use includes 60 % residential, 20 % commercial, and 20 % industrial areas. The impervious area of the developed land use type is determined based on the average impervious areas of urban land uses: 32 %, 20 %, and 72 % for residential, commercial, and industrial, respectively. The average impervious area percentages of the developed land use type (35 %) are obtained by weighting the percentages of urban land uses. In this study, each sub-watershed has 4,000 ha (10,000 ac). Thus, when all areas in a sub-watershed are covered by development land use with no BMPs, the impervious surface becomes 1,400 ha (3,500 ac) and the pervious surface is 2,600 ha (6,500 ac). This means that 1,400 ha (3,500 ac) is the maximum size to be replaced with BMPs in a sub-watershed in this study. In the HSPF model system, when BMPs reach 1,400 ha (3,500 ac) in a 4,000 ha (10,000 ac) watershed, all surface areas become pervious. Existing green areas attached to structures - grassed front or back yards - remain untouched, not replaced by BMPs.

In a PERLND module of HSPF, lower zone evapotranspiration parameter and interception storage capacity are determined to be constant because monthly variances are not an issue in this study. The values for sensitive parameters that characterize the hydrologic behaviors of the theoretical watershed are given in Table 1. The sensitive parameters are key variables identified in HSPF modeling to obtain an optimal agreement between the simulation output and the monitored output (USEPA, 2002b; USU, 2003). These are identified for BMPs and development uses.

Table 1 Sensitive parameters that characterize the hydrologic behaviors of the watershed

Sensitive parameter	Watershed	
	BMPs	Development
Lower zone nominal storage (LZSN, mm)	43.18	38.10
Index to the infiltration capacity of soil (INFILT, mm/hr)	3.81	2.03
Interception storage capacity (CEPSC, mm)	62.23	56.39
Upper zone nominal storage (UZSN, mm)	30.48	12.70
Interflow recession parameter (IRC, unitless)	0.85	0.85
Interflow inflow parameter index (INTFW, unitless)	4.00	2.50
Lower zone evapotranspiration parameter index (LZETP, unitless)	0.37	0.30

When constructing the meteorologic input, the minimum input time series data requirements depend upon the HSPF modules to be used. Precipitation and potential evaporation (PE) are the minimum requirements to run HSPF hydrology. The other weather data including temperature, wind speed, solar radiation, potential, dew point temperature, and cloud cover are required for other purposes, such as sediment, water quality, and plankton simulations (Bicknell et al., 2001). In this study, a minute interval precipitation is provided. Zero values are provided for PE in order to minimize variables. To construct meteorologic input for HSPF, a synthetic rainfall hyetograph is developed by using the Natural Resource Conservation Service (NRCS) rainfall pattern with a one minute increment. In determining the duration and intensity of the input rainfall event, a 100 year 24 hour design storm is used to make the rainfall event consistent with the standard design flooding probability (0.01 percent) of the National Flooding Insurance Program (NFIP) and flood control systems. For the storm region, the Blackberry Creek watershed, Illinois, US is selected to have a relevant storm event to the referenced infiltration characteristics. The designed storm occurs only on the 2nd day of the simulation period. The storm has the highest rainfall of 70.60 mm (2.78 in) at 12:00 and total rainfall is 165.10 mm (6.50 in) in the storm day.

3. Estimating Storage Volumes and Avoided Costs

To estimate storage volumes demanded from the BMP allocation scenarios, a NRCS regression equation method is used: Vs = Vr [(1.291 x (1 - Qo / Qi)0.753) / (ti / tp)0.411], where Vs = storage volume (m^3), Vr = inflow hydrograph (m^3), Qi = peak inflow rate (m^3/s), Qo = allowable peak outflow rate (m^3/s), ti = time base of the inflow hydrograph (hr), and tp = time peak of the inflow hydrograph (hr).

For the inflow hydrograph, stream outflow hydrographs from the allocation variances are used with the assumption that open channel streams go directly into a detention pond. Time base of the inflow hydrograph and time peak of the inflow hydrograph are read from the HSPF modeling. In order to find the time base, the model simulation duration is extended until the time t when outflow becomes zero. However, in fact, since very low outflow continues for the long period time, the time when outflow becomes constant and nearly zero is used. Several peak inflow rates are generated from the HSPF modeling. The inflow hydrograph volumes are estimated from the inflow rates and times. A stream outflow hydrograph from the pre-development condition is determined to be a target outflow release rate or allowable peak outflow rate to be controlled and met by the detention ponds, as many municipalities mandate in their ordinances. It implies that post-development peak flows do not exceed pre-development peak flow rates for one or more storm frequencies at specified points along a channel.

The pre-development condition is simulated by using HSPF. Infiltration parameters for urbanization are applied to all watersheds, but all impervious urban lands are converted to pervious lands in order to represent that there is no urban development. Pre-development conditions are generally expected to generate less stream volume and flow rate than post-development conditions in a given duration of time because more water is stored in upper zone (UZSX) and lower zone nominal storages (LZSX) in the watershed due to the extended size of infiltrated surface areas.

To estimate regional detention pond costs, the equation developed by Center for Watershed Protection (CWP, 1997) is used: TC = 23.07 x Vs0.705, where TC is total cost ($), and Vs is storage volume (ft3). It indicates that the log-transformed costs and volumes are related using power analysis. According to the CWP, (1) the cost includes excavation, control structure, appurtenances, design/engineering, sediment control, and landscaping costs, (2) the associated correlation coefficients were examined to determine the validity of the relationship between total volume and total cost (R2=0.8). The avoided costs are obtained by subtracting the estimated costs of individual scenarios from the greatest cost among them. The difference would be the savings which the scenarios generate.

4. Hydrologic Characteristics of the Designed Watershed

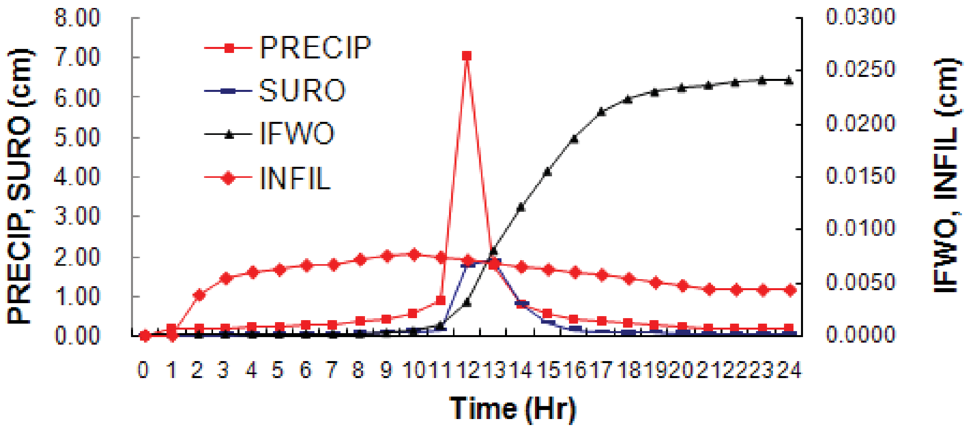
The overall watershed model and data admissibility are examined through hydrologic behavior tests due to the absence of a real policy site. With regard to the parameter values stored in HSPF, Johnson et al. (2003) reported that comparing individual parameters of the model with field measurements is impossible. They argued that many of the storages used by HSPF are not defined explicitly and cannot be directly measured due to the conceptual nature of its parameters. However, the simulated streamflow by the HSPF shows an integral response with several combinations of lumped parameter values (Beven and Freer, 2001; Jacomino and Fields, 1997). The HSPF user manual (USU, 2003) explains that watershed models are developed, in practice, by entering site specific values with the default storage values in HSPF and performing calibration through sensitive parameters. It indicates that the default storage values (Table 2) are recommended to be maintained in the system for better simulation performance. Specifically, the default storage values play roles as system drivers to increase simulation capability.

Table 2 The Default Values in Storage Parameters in HSPF

Storage parameters storing default values	Default storage value
Interception storage (CEPS)	0.01
Surface storage (SURS)	0.01
Upper zone storage (UZS)	0.30
Lower zone storage (LZS)	1.50
Interflow storage (IFWS)	0.01
Active groundwater storage above base elevation (AGWS)	0.01
Retention storage (RETS)	0.01
Surface storage (SURS)	0.01

Fig. 2 shows that the hypothetical watershed has the proper hydrological behaviors that as precipitation (PRECIP) increases, surface runoff (SURO) and interflow (IFWO) increase; that as water moisturizes the soils, infiltration rate (INFIL) decreases and interflow (IFWO) increases. In general, actual hydrologic phenomena are characterized by great variability, randomness, and uncertainty. Thus, it is noted that frequency analysis is essential to analyzing the hydrologic characteristics of real watersheds (Wurbs and James, 2002). However, frequency analysis is not employed in this study because the hypothetical watershed has a deterministic, controlled environment in which to model the hydrologic behaviors of BMPs with only the 100 year 24 hour rainfall event. It means that whenever the designated storm occurs with the given duration and intensity of rainfall, the watershed will respond identically all the time. Thus, simulated peak flows are interpreted by the first order approximation.

Figure 2 The Hydrologic Characteristics of the Hypothetical Watershed



Ⅴ. Experiments

Two experiments are conducted. In experiment 1 (E1), a fixed allocation is simulated. The E1 is intended to illustrate the differences of BMP locational strategies between upper, middle, and down streams in the watershed (Fig. 3). Further exploration is specified in experiment 2 (E2) to observe whether both horizontal and hierarchical variations exist in multiple watersheds. The BMP locations are differentiated horizontally and hierarchically (Fig. 4). In both E1 and E2, the total BMP area remains constant in the whole watershed, regardless of distribution. E1base represents development conditions without BMPs. The rest of the scenarios represent development conditions with BMPs. For all experiments, peak flows are recorded at each watershed. However, interpretation is focused on the peak flow at the final outlet.

Figure 3 Experiment 1 (E1): fixed spatial distribution scenarios. The shaded areas indicate the location of BMPs.

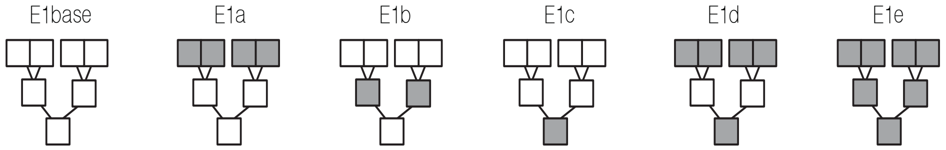
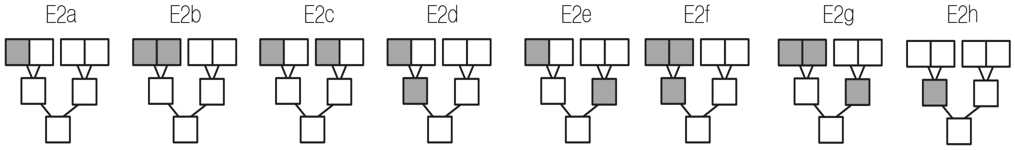


Figure 4 Experiment 2 (E2): varied spatial distribution scenarios. The shaded areas indicate the location of BMPs.



Ⅵ. Results

1. Changes in Stream Peak Flows

A focus is made at RCH 1, which is the final outlet of the entire watershed. E1 results show that E1a generates the lowest stream peak flow at the watershed outlet (Table 3). It implies that distributed BMPs in the upper sub-watershed are most effective in peak flow reduction at a watershed scale (790 m^3/s). On the other hand, centralized BMPs (E1c) in the downstream are observed to be the least effective alternative at a watershed scale (841 m^3/s). However, it should be noted that locating BMPs at all points of runoff generation (E1e) is not the best alternative, although it is the most common method of distributing BMPs (813 m^3/s). It appears that partial distribution is better than entire distribution in locating BMPs at a watershed scale. So, the most common practices - BMPs in the downstream (E1c) and distributed BMPs in the entire watershed (E1e) - are found to be less effective alternatives. From a peak time perspective, it can be seen that no matter where BMPs are located, they are effective in flow velocity reduction. All peak flows occur between 14:18 and 14:29 (hours: minutes) at a watershed scale. However, it is apparent that the lowest stream peak flow does not necessarily occur with the longest travel time (Table 4). In E2, all peak flows occur at the time between 14:15 and 14:26 (hours: minutes) at a watershed scale (Table 5). It is observed that partially distributed BMPs (E2b) in the upper watershed are most effective (787 m^3/s), and that centralized BMPs (E2a) are not effective even in the upper watershed (816 m^3/s) (Table 6).

Pragmatically, the best choice would differ depending on the target constituent or watershed to be managed. However, for regional stormwater management primary attention tends to be given to peak flow reduction at the final watershed outlet. If this is the case, as observed in E1 and E2, partially distributed BMPs located in the upper reaches of the watershed are the best BMP location and distribution for peak flow reduction at a watershed scale.

Table 3 Peak Flow from E1 Scenarios (m^3/s)

Location \ Scenario	E1base	E1a	E1b	E1c	E1d	E1e
Upper stream (RCH 4-7)	192	138	192	192	165	182
Middle stream (RCH 2-3)	464	379	396	464	422	413
Down stream (RCH 1)	934	790	799	841	816	813

Table 4 Peak Time in the Day of a Single Storm (hours: minutes) from E1 Scenarios

Location \ Scenario	E1base	E1a	E1b	E1c	E1d	E1e
Upper stream (RCH 4-7)	13:14	13:20	13:14	13:14	13:17	13:16
Middle stream (RCH 2-3)	13:44	13:48	14:00	13:44	13:45	13:52
Down stream (RCH 1)	14:18	14:19	14:25	14:29	14:25	14:27

Table 5 Peak Time in the Day of a Single Storm (hours: minutes) from E2 Scenarios

Location \ Scenario	E2a	E2b	E2c	E2d	E2e	E2f	E2g	E2h
RCH 7	15:04	13:46	13:46	13:46	13:46	13:26	13:26	13:15
RCH 6	13:15	13:46	13:15	13:15	13:15	13:26	13:26	13:15
RCH 5	13:15	13:15	13:46	13:15	13:15	13:15	13:15	13:15
RCH 4	13:15	13:15	13:15	13:15	13:15	13:15	13:15	13:15
RCH 3	13:30	13:56	13:45	13:57	13:45	13:59	13:54	14:07
RCH 2	13:45	13:45	13:45	13:45	13:53	13:45	13:49	13:45
RCH 1	14:17	14:15	14:19	14:26	14:22	14:19	14:22	14:26

Table 6 Peak Flow from E2 Scenarios (m^3/s)

Location \ Scenario	E2a	E2b	E2c	E2d	E2e	E2f	E2g	E2h
RCH 7	12	86	86	86	86	120	120	192
RCH 6	192	86	192	192	192	120	120	192
RCH 5	192	192	86	192	192	192	192	192
RCH 4	192	192	192	192	192	192	192	192
RCH 3	323	292	377	309	377	306	351	328
RCH 2	464	464	377	464	394	464	416	464
RCH 1	816	787	790	793	793	790	793	793

In general, major factors affecting travel time and peak flow rate are surface roughness, watershed and channel slope, and land use. However, in this hypothetical watershed, these are held constant except for differences in the time and location of infiltration between sub-watersheds. Therefore, it appears that peak timing between sub-watersheds caused by the cumulative impact of flows is the factor resulting in different streamflow.

2. Changes in Potential Cost Savings

As avoided costs, potential cost savings from the scenarios with 1,416 ha (3,500 ac) BMPs are estimated at a watershed scale (Table 7). Reduced peak streamflow (m^3/s) increases savings in regional detention pond cost. The biggest cost saving can be obtained from E2b, and the benefits from the avoided cost are $ 10,671 at a watershed scale. It is found that a hydrologically beneficial strategy is an economically beneficial strategy as well although the benefits are not high. Overall, cost savings range from $ 3,985 to $ 10,671 at a watershed scale. In a word, the economic benefit of 1,416 ha (3,500 ac) BMPs - which is the maximum size of BMPs to be implemented in a single sub-watershed - can differ depending on the allocation strategy of BMPs.

Table 7 Storage Volumes and Potential Cost Savings

Scenario	Vr	Qo	Qi	Ti	tp	Vs	TC	CS
E1base	453,069	95	934	1,056	14.18	91,754	897,443	0
E1a	453,069	95	790	1,056	14.19	90,351	887,743	9,700
E1b	453,069	95	799	1,056	14.25	90,612	889,555	7,888
E1c	453,069	95	841	1,056	14.29	91,177	893,458	3,985
E1d	453,069	95	816	1,056	14.25	90,804	890,882	6,561
E1e	453,069	95	813	1,056	14.27	90,823	891,014	6,429
E2a	453,069	95	816	1,056	14.17	90,594	889,430	8,013
E2b	453,069	95	787	1,056	14.15	90,210	886,772	10,671
E2c	453,069	95	790	1,056	14.19	90,351	887,743	9,700
E2d	453,069	95	793	1,056	14.26	90,569	889,254	8,189
E2e	453,069	95	793	1,056	14.22	90,464	888,530	8,913
E2f	453,069	95	790	1,056	14.19	90,351	887,743	9,700
E2g	453,069	95	793	1,056	14.22	90,464	888,530	8,913
E2h	453,069	95	793	1,056	14.26	90,569	889,254	8,189

Note: Vr: inflow volume (streamflow) (m^3); Qo: allowable peak outflow rate (m^3/s) (Qo is the standard outflow rate for all scenarios; it is estimated by the pre-development conditions); Qi: peak inflow rate (m^3/s) (these are outflow rates from each scenario; these rates will be reduced to Qo by regional detention ponds); ti: time base of the inflow hydrograph (hr); tp: time to peak of the inflow hydrograph (hr); Vs: storage volume (m^3); TC: total cost ($); CS: cost saving ($).

Ⅶ. Policy Implications

As is well known, the area of impervious surface in a watershed has been proposed as a policy variable for stormwater management. For example, stormwater utility fee systems use the total impervious area of each land parcel for a stormwater utility rate structure. The utility structure might be improved by incorporating the BMP allocation strategy. The location and unit cost ($/ac) can be introduced as a policy variable and its weight, respectively.

Table 8 Incremental Costs between the Spatial Distribution Scenarios

Scenario	Total cost ($)	Incremental cost ($)	Incremental unit cost ($)
E1base	897,443	10,671	0.15
E1a	887,743	971	0.01
E1b	889,555	2,783	0.04
E1c	893,458	6,686	0.10
E1d	890,882	4,110	0.06
E1e	891,014	4,242	0.06
E2a	889,430	2,658	0.04
E2b	886,772	0	0.00
E2c	887,743	971	0.01
E2d	889,254	2,482	0.04
E2e	888,530	1,758	0.03
E2f	887,743	971	0.01
E2g	888,530	1,758	0.03
E2h	889,254	2,482	0.04

Note: Incremental unit cost ($/ac) = incremental cost ($) / 70,000 (the entire watershed in ac).

Incremental costs are estimated for all scenarios from E1base to E2h (Table 8). Total costs are the budgeting estimates in constructing regional detention ponds based on each scenario to meet the pre-development site hydrology. Incremental costs are the extra costs resulting from the scenarios, and these are measured by subtracting the smallest total cost (E2b) from the individual total costs (scenarios). Table 8 indicates that E1base scenario costs $ 10,671 more than the E2b scenario to meet the given flow standard (outflow rate of 95 m^3/s for all alternatives. See Table 7). Similarly, E1c costs $ 6,686 more than E2b, and adopting E1d results in a budget loss of $ 4,110, which can be saved by using E2b. In terms of the incremental unit cost, E1c costs $0.10 more per 0.4 ha (1 ac) across the entire watershed.

In illustrating a policy frame, a geographic setting for trade-off is defined between upstream (branch) and downstream (mainstem) lands. It is a widely accepted hierarchy of river system to divide a watershed into branch and mainstem lands.

The idea is that, in general, additional costs will be collected from the upstream properties, and the revenue will be invested in upstream lands to increase upstream stormwater management services. The revenue will be used for public programs and not for refunding land owners. The logic is (1) that upstream management is most efficient in reducing streamflow rates both downstream and upstream ; and (2) that upstream lands generate negative externalities (e.g. treatment costs) to downstream lands due to the negative cumulative flow impact. Therefore, upstream lands are responsible for the negative externality.

Three conditions could be established in collecting fees from property owners with the assumption that a stormwater utility fee system is operated in the watershed. E1c and E1e represent BMPs in the mainstem lands and the entire watershed, respectively.

In the first condition - BMPs in branch - utility fees will be collected from all property owners in the watershed based on the existing fee system, with no additional costs. In the second condition - BMPs in the entire watershed - additional costs will be charged to upstream property owners. In applying the unit cost, E1e (unit cost: $ 0.06/ac) will be referenced, which illustrates the BMPs in the entire watershed. Each upstream property owner will be responsible for the existing utility fee based on the surface imperviousness, and for the additional costs from their properties (incremental unit cost: $ 0.06/ac) and from downstream properties (sum of additional costs from downstream properties divided by the number of acres in upstream). The responsibility fee will not be increased for the downstream property owners at all. In the third condition - BMPs in the mainstem - additional costs will be charged to upstream property owners. In applying the unit cost, E1c (unit cost: $ 0.10/ac) will be referenced, which illustrates the BMPs in the mainstem only. Upstream property owners will pay the basic utility fee and the additional costs from their properties and downstream properties as well. However, the responsibility fee will not be increased for the downstream property owners. This modified utility fee system could be administered by a regional authority although establishing a new authority or district might require demanding political processes. Also, it will be necessary to consider the direct and indirect costs. If transaction costs, including the costs of assessing and collecting fees, exceed revenues, it will not be a feasible policy.

Ⅷ. Discussion

The major hydrologic functionality of BMPs is targeted to increasing infiltration to the ground because infiltration is the most interesting and generalizable indicator in relating BMPs to the ground surface condition in most cases. The infiltration capacity of BMPs is constant within the watershed no matter where they locate in this experiment. Therefore, the deterministic factor driving hydrologic differences between the allocation strategies is the size of the BMPs in sub-watersheds while the total area of the BMPs remains constant at the entire watershed. By changing the size of the BMPs in sub-watersheds, each sub-watershed can have different flow contribution to downstream in its time and volume. It illustrates the hydrologic effect of spatial distribution of BMPs by simulating the cumulative impacts of flow between sub-watersheds.

Regarding the hydrologic simulation and economic valuation, the main critique is that outflow rate and cost variations are insignificant (1) between implementing BMPs (scenarios) and not implementing BMPs (E1base) and (2) between scenarios. In this experiment, the infiltration functionality of BMPs is strictly controlled by model parameters. The infiltration performance of BMPs can be much bigger or smaller depending on parameter values regardless of their location and size. Consequently, the impacts of BMPs can be underestimated in their actual hydrologic performance. The underestimation results in the similar outflow rate and cost variations between implementing BMPs and not implementing BMPs; and between scenarios. Also, it seems that the net costs for BMP implementation overrides the benefits reported in this experiment. However, it should be noted that this study uses the most generalizable indicator - cost saving from the reduced detention pond volume caused by peak flow attenuation - resulting in the minimum benefit associated with BMPs. Presumably, actual benefits would be much larger in real project sites by including more benefit indicators available in particular space and time. These indicators are not limited to water quality protection, instream biotic integrity, reduced urban heat island effect, reduced storm drainage system cost, increased groundwater recharge, and increased property values.

Ⅸ. Summary and Conclusion

It is difficult to measure the benefits associated with the allocation strategy of BMPs in a general term when the benefits are highly correlated with non-market services and the services are heavily affected by site specific characteristics. Thus, it would be feasible to illustrate the minimum potential benefit from the most common and generalizable variable across project sites. This paper attempts to find the desirable allocation of sub-watershed level BMPs for peak flow reduction at a watershed scale. Major findings are that when total size of BMPs is constant in the entire watershed, (1) it is most effective to have aggregated BMPs in some upper sub-watersheds (787 m^3/s) while the BMPs in either the mainstem sub-watershed (841 m^3/s) or a single sub-watershed (816 m^3/s) are the least effective choices for peak flow attenuation at a watershed scale; (2) savings exist between allocation differences and reduced peak flow increases cost savings. The largest saving is found in the strategy of aggregated BMPs in some upper sub-watersheds. This study shows the possibility that peak flow attenuation can be achieved through the appropriate location and distribution strategy of BMPs; that BMP allocation strategy might be considered as a potential policy variable. These findings, however, call for follow-up site specific case studies revisiting the watershed scale impact of BMP allocation. Then, it will be argued that location and extent of decentralization are considerable policy variables for an alternative stormwater management policy at a watershed scale.

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