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Optimal volume of non-point sources management detention considering spatio-temporal variability of land surface moisture condition

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ABSTRACT

This study presents the method to estimate the optimal volume of a non-point sources (NPS) management detention considering spatio-temporal variability of urban land surface moisture condition. In order to consider statistical characteristics of rainfall events, 3-parameter mixed exponential probability density function (PDF) is applied, and rainfall events are transformed to runoff events through Natural Resources Conservation Service–curve number method. Urban drainage catchment is divided into square-type grid cells, where runoff curve number is estimated by cells. Using the analytical model developed previously with derived probability distribution theory, the PDF of rainfall event depth is transformed to the PDF of stormwater depth. By cells, in consideration of changes in antecedent soil moisture condition and spatial variations in CN of drainage catchment, stormwater capture curve that can represent the drainage area is drawn and from which the optimal volume of a NPS management detention is estimated.

Keywords: Detention; Non-point sources management; NRCS–CN; Probability density function; Stormwater capture curve

1. Introduction

Researches on rainfall-runoff have been mainly concentrated on extreme cases (e.g. flood and drought) until now. The reason of such concentration is that social interest on rainfall-runoff is mainly on prevention of flood. Performance of researches on rainfall-runoff for prevention of flood can be applied for flood management system properly, but it is deemed unreasonable to directly apply such performance to non-point sources (NPS) management system [1].

Stormwater quality control facilities are designed to manage NPS by reducing the pollutants carried by stormwater. The amount of stormwater to be captured is a key factor in the design of NPS control detentions. When the design capacity is too large, construction and maintenance costs are increased, so that the project is not economical. When it is too small, a large number of rainfall events exceed the capacity. Different from point sources, NPS emission location is

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unclear, and they are mainly emitted during rainfall events which have strong stochastic characteristics. Such features result in substantial high temporal and spatial variations in NPS behavior, and thereby the quantification of NPS emission is very difficult. Therefore, to determine optimal volume of the NPS control detention is highly difficult [2].

Pursuant to Article 53 of the Water Quality & Aquatic Ecosystem Conservation Act, Ministry of Environment in Korea regulates that the volume of NPS control detentions should be 5 mm times the corresponding drainage area [3]. However, there is lack of scientific evidence supporting the aforementioned 5 mm stormwater runoff volume, there are some opinions that clearer explanation is deemed required [1]. Also, current determination of NPS control detentions is applied by the single design storm event rather than long-term continuous rainfall event sequence approach, but the single design storm event has been developed in a purpose of prevention of extreme flood events, and therefore it is not suitable for the purpose of management of NPS for common rainfall events. As a result of analysis on rainfall data of Cheongju Branch of the Korea Meteorological Administration, the fact that the rainfall event exceeding 25 mm stands at less than 20% out of entire events exhibits that design of NPS control detentions in consideration of long-term continuous rainfall sequence approach is deemed necessary rather than single design storm event approach based on flood analysis. In past study, [4] also found similar results of rainfall frequency distribution for Busan Branch of the Korea Meteorological Administration.

When looking into researches on NPS control detentions until now, stochastic representation of overflow risk of NPS control detentions has mainly been focused [2,5–8]. Especially, 3-parameter mixed exponential probability density function (PDF) was adopted for better reflection of rainfall phenomenon of Korea in Ref. [1]. In case of rainfall-runoff transformation, Natural Resources Conservation Service–curve number (NRCS–CN) method has been used to explain non-linear characteristics of rainfall-runoff process and to determine an appropriate detention volume when applying for urban drainage catchments of Korea having complex land use characteristics.

However, Kim [1] shows problems that when deriving stormwater capture curve, spatially averaged CN value, which is constant during a year, has been applied, so that their research fails to find out important advantages of NRCS curve number, which can considers different infiltration capacity in accordance with seasons and antecedent inter-event time. In other words, even the rainfall event depth is same, rainfall depth that can be captured by drainage catchment may differ in accordance with seasons and antecedent inter-event time, and thereby stormwater capture curve derived from this can be different accordingly. Also, Kim [1] determined CN value by overlapping soil map and land use map of drainage catchment, and then applied same CN value for entire drainage catchment by using area-weighted average method to derive stormwater capture curve. However, due to high spatial variability of CN value, stormwater capture curve derived from spatially averaged CN value cannot be said to be consistent with average stormwater capture curve derived by CN values by soil map-land use map patches.

Hence, this study is purposed to solve above-mentioned two problems. In other words, by reflecting temporal and spatial variations of CN value, we would like to derive stormwater capture curve and determine optimal volume of the NPS control detentions.

2. Materials and methods

2.1. Study area

Jeungpyeong drainage catchment is our study area (Area of drainage catchment: 205.75 ha) (Fig. 1). When examining the land use conditions of Jeungpyeong drainage catchment, most of land is used for residential site, commercial site, road, and parking lots, most of which are characterized as urban land use, and according to city development plan for surrounding area, additional urbanization and industrialization will result in increase in roads, traffic volume, and thereby stormwater runoff will be increasing. Consequently, it is likely that contaminant load from NPS will be intensified. Therefore, the provincial government is planning to install NPS pollution reduction facilities around the outlet of the catchment. The drainage catchment is divided by 30 × 30 m and result of CN-II of each cell is indicated, and Fig. 2 shows its spatial frequency distribution. It can be noticed that stormwater capture curve can be different by cells attributable to such spatial distribution.

2.2. Determination of IETD

The analytical probabilistic models for stormwater management require the statistical analysis of individual storm events from a long-term rainfall record. The Inter-Event Time Definition (IETD) is used to isolate an individual storm event from a long-term rainfall record. For further details of the IETD, [3] can be referred to (Fig. 3).

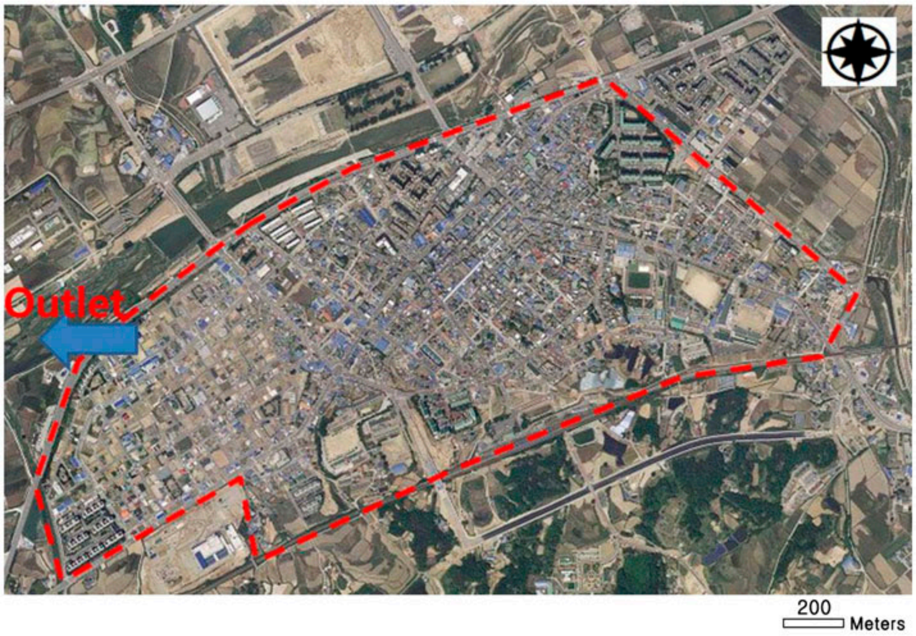

Fig. 1. Jeupyeong urban drainage catchment (205.75 ha).

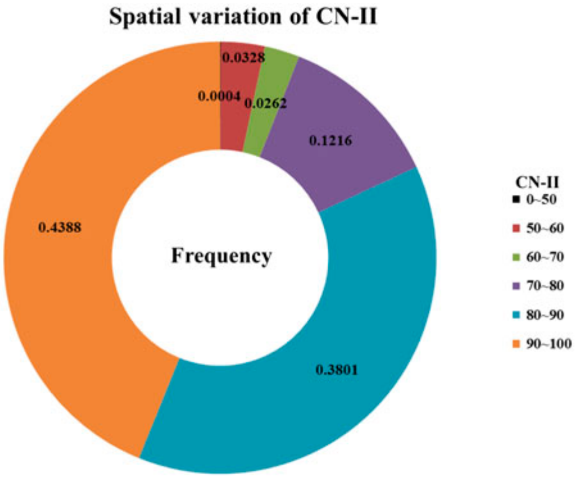

Fig. 2. Spatial variation of curve number with AMC-II.

Approaches to defining the IETD in order to discretize a rainfall record into independent events are through an autocorrelation analysis, the analysis of the coefficient of variation, and examination of the relationship between the IETD and the average annual number of rainfall events [2]. In this study, the analysis of coefficient of variation is applied. In such an approach, the probability density of inter-event times is assumed to be adequately represented by the single-parameter exponential distribution [9,10] Therefore, the coefficient of variation is unity. The IETD can then be selected as that which results in the sample coefficient of variation for inter-event times equal or approximately equal to unity. The result of applying of this into precipitation data for 10 years (2000–2009) of Cheongju Branch of the Korea Meteorological Administration is shown in Fig. 4.

In case of Cheongju Branch, it can be noticed that 10-h is deemed appropriate for the IETD.

Also, this concept of the IETD is highly meaningful in terms of securing hydraulic retention time and drainage time of a NPS management detention, and reflecting this to design. That is, when designing a NPS control detention with 10-h IETD, there will not be subsequent rainfall events within at least 10 h after a certain rainfall event is terminated, therefore retention, treatment, and drainage of stormwater in the NPS control detentions are available. In other words, when taking into account of IETD, which is a meteorological concept, in the standpoint of operation of NPS control detentions, this can be conceptualized as the time of retention, treatment, and drainage.

2.3. *Analysis on rainfall event depth*

In this study, as the PDF of total rainfall event depth when a storm event occurs, 3-parameter mixed exponent PDF was used, and 3-parameter mixed exponent PDF concerning rainfall event depth v is as shown below.

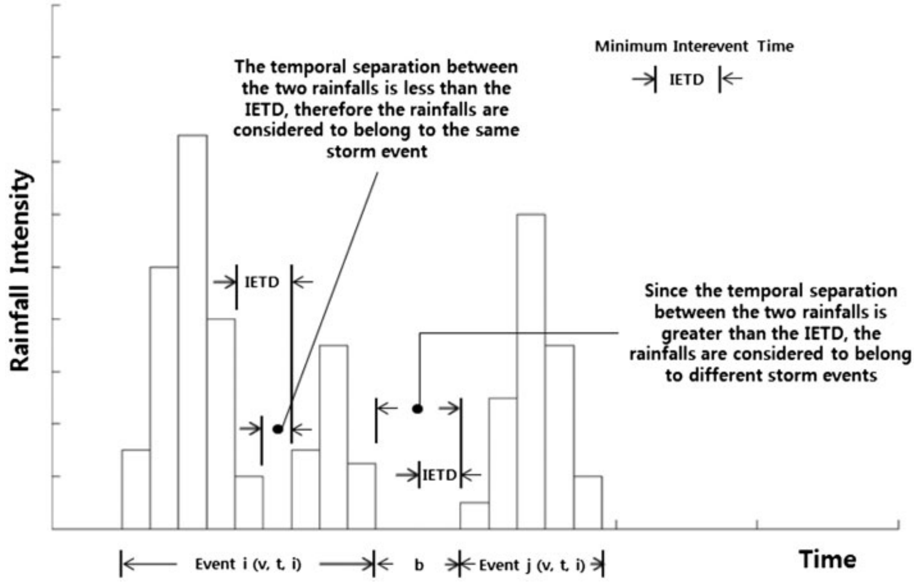

Fig. 3. Definition of IETD [7].

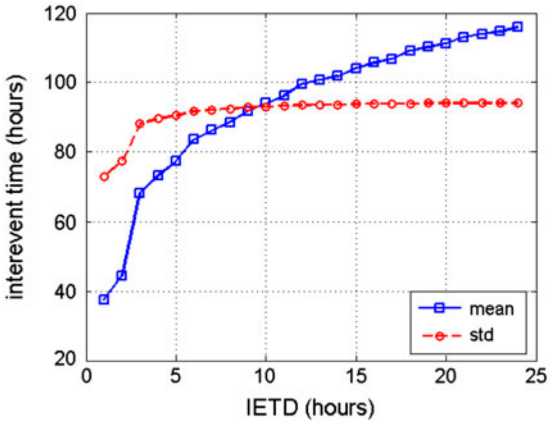

Fig. 4. Determination of IETD.

$$f(V) = \frac{\gamma}{\alpha}e^{-v/\alpha} + \frac{(1-\gamma)}{\beta}e^{-v/\beta}, \qquad \text{for} \quad v \geq 0 \tag{1}$$

where α, β, and γ are parameters of 3-parameter mixed exponent PDF, and they can be estimated by using the moment method [1]. Cumulative probability distribution function (CDF) is as specified below.

$$P_V(0 \leq v \leq V) = 1 - \gamma e^{V/\alpha} - (1-\gamma)e^{-V/\beta} \tag{2}$$

2.4. Analysis on runoff

When NRCS–CN is used for rainfall–stormwater relationship, runoff (mm) of stormwater in a catchment can be indicated as specified Eq. (3) [11].

$$V_0 = 0, \quad \text{for} \quad V < V_i$$

$$V_0 = \frac{(V - V_i)^2}{V - V_i + S}, \quad \text{for} \quad V \geq V_i \tag{3}$$

V_0 refers to runoff of stormwater (mm), V refers to rainfall event depth (mm), and V_i refers to initial abstraction (mm), and its value is recommended as $0.2S$ [11]. It is noticeable that it's fairly well-known now that the observed curve numbers almost always vary with rainfall event depth. Small storms have high CNs. It is the big population of small storms (with high CNs) that concern here. Thus, in this study, the value of initial abstraction is set to be 2.5 mm in order for small rainfall events to generate stormwater.

In Eq. (4), the potential maximum soil moisture retention after runoff begins, S is as shown below [11].

$$S = \frac{25{,}400}{\text{CN}} - 254 \tag{4}$$

Here, CN refers to NRCS's runoff curve number, whose value is assigned in accordance with soil types and land cover conditions. This, as a table, is shown in various hydrology textbooks (Hawkins [12]). In Korea, through the table to determine CN are the most universally applicable. In our study, such method is applied in terms of increasing the applicability of research. However, although there are differences in how CN values calculated, there are not any changes in the methodology proposed in this study. Such CN value table is with AMC II (i.e. CN-II), and CN value should be adjusted to meet antecedent soil moisture condition (AMC) actually corresponding to actual soil moisture condition. As for NRCS, in accordance with 5-d antecedent rainfall standard value which has been determined by seasons, AMC is divided into I, II, III, and presents CN-I and CN-III that responds to CN-II. For further details, Chow [13] can be referred to. Result of analysis on AMC's relative frequency on 840 rainfall events of Cheongju Branch for recent 10 years shows that AMC-I was 76%, AMC-II was 11%, and AMC-III was 13% in case of Cheongju Branch.

When using the derived PDF theory [1], CDF of stormwater depth can be derived from rainfall-runoff model (Eq. (3)) and CDF of rainfall event depth (Eq. (2)) as shown below.

$$G(V_0)=\frac{\gamma e^{-V_i/\alpha}+(1-\gamma)e^{-V_i\beta}-\gamma e^{-k/\alpha}-(1-\gamma)e^{-k/\beta}}{\gamma e^{-V_i\alpha}+(1-\gamma)e^{-V_i\beta}} \tag{5}$$

where k is calculated as shown below.

$$k=\frac{V_0+2V_i+\sqrt{V_0^2+4V_0\cdot S}}{2} \tag{6}$$

Benjamin [14] outlined derived probability theory and gave examples of its application. Derived probability distribution models can be an effective method of depicting the continuous performance of urban drainage systems and have been employed in various applications [9].

In Eq. (5), if the capacity of a NPS detention facility is designed as V_0, $G(V_0)$ refers to capture rate when a stormwater event occurs. For example, the meaning that $G(V_0)$ is 0.7 is that when capacity of a detention facility is designed to be V_0, then 7 out of 10 stormwater events can be captured by a NPS control detention. It can be seen that stormwater capture curve $G(V_0)$ is determined by characteristics of rainfall event depth of drainage catchment (average, standard deviation, skewness) and characteristics of drainage catchment (S, i.e. CN value), and capacity of a detention facility (V_0).

2.5. *Application of spatio-temporally varied CN values in view of antecedent soil moisture and spatially heterogeneous condition*

Even in case of same rainfall, CN value is different in accordance with AMC (Refer to Fig. 2), and this results in different capture rate of drainage catchment, thereby stormwater capture curve is influenced accordingly. Also, CN value is calculated from soil map and land use map of drainage catchment, there are various CN values in accordance with locations of drainage catchment (Refer to Fig. 2), and thereby the type of stormwater capture curve will be different.

In this section, CN value of drainage catchment is calculated as shown below with consideration of AMC from 5-d antecedent rainfall of each event.

$$\begin{aligned}G(V_o(i,j))=\;&\mathrm{p}[\mathrm{CNI}(i,j)]\times G(V_o(i,j),\mathrm{CNI}(i,j))\\&+\mathrm{p}[\mathrm{CNII}(i,j)]\times G(V_o(i,j),\mathrm{CNII}(i,j))\\&+\mathrm{p}[\mathrm{CNIII}(i,j)]\times G(V_o(i,j),\mathrm{CNIII}(i,j))\end{aligned} \tag{7}$$

CNII(i, j) refers to CN-II of a cell of (i, j) when dividing drainage catchment into a constant resolution ($30\,\mathrm{m}\times 30\,\mathrm{m}$ for this study), and p[CNII(i, j)] is the probability that AMC of a certain rainfall event is under AMC-II. G(V_0 (i, j), CNII(i, j)) can be derived using Eq. (5) with CNII(i, j).

3. Results and discussion

3.1. *Application of rainfall—runoff*

As a result of time series analysis on 10-h IETD of Cheongju Branch for recent 10 years, it was found out that annual average number of rainfall events was 84.

Values of parameters of 3-parameter mixed exponent PDF, which are estimated from the time series analysis on rainfall event depth for recent 10 years of Cheongju Branch, are as the following: α is 60.9205 mm, β is 7.2288 mm, and γ is 0.1425 mm. This means that there are two components for different storm groups as defined by season. Most of storm events (85.75%) are thought to be from the smaller storm group. The Fig. 5 shows cumulative frequency distribution of rainfall event depth (Observed) and 3-parameter mixed exponent CDF (exp3). For reference, 1-parameter exponent CDF (exp1), which is generally used, is also shown. As mentioned by Kim [1], it can be noticed that 3-parameter mixed exponent CDF better exhibits observation time series than 1-parameter exponent CDF.

3.2. *Application of spatial and temporal average CN*

In this section, as the research of Kim [1], result of stormwater capture curve when CN value is constant temporally and spatially, and the optimal volume of NPS control detentions to be calculated there from is designated.

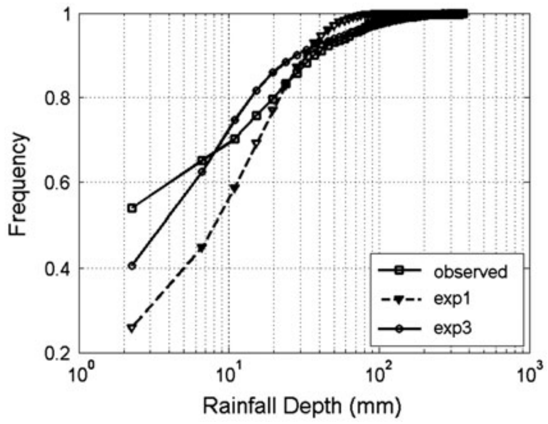

Fig. 5. Cumulative probability distribution of rainfall depth.

Fig. 6 shows stormwater capture curve for spatially averaged CN-II 86.87 of Jeungpyeong drainage catchment. The stormwater capture curve ranges from 0 to 100% in accordance with capacity of NPS control detentions, and in the case when the capacity of the facilities is increasing, the curve gradually reaches to 100%. It is noticeable that to capture all the stormwater generated in a catchment through NPS control detentions is impossible practically, so the criteria for maximum stormwater capture rate is deemed necessary. In this study, the maximum capture rate is set as 90%. This bespeaks that the capacity of NPS control detentions has been determined so that 9 out of 10 stormwater events can be captured.

In Fig. 7, the maximum capacity of NPS control detentions of Jeungpyeong drainage catchment, which corresponds to 90% of stormwater capture rate, is calculated as 19.9948 mm, and this means that rainfall can be captured up to 41.9519 mm when CN value is constant. In other words, the capacity of optimal NPS control detentions will be determined within a range 0–19.9948 mm, which corresponds to 0–90% of stormwater capture range. Accordingly, we would like to consider the both extreme cases of the stormwater capture curve. Note that the probability that the rainfall event depth is less than 41.9519 mm is 0.9258. As the first extreme case, when the NPS control detentions are not installed, no expense will be required, but stormwater cannot be captured, thereby efficiency of installation of NPS control detentions is zero. As the second extreme case, when the NPS control detentions with maximum capacity are installed, the stormwater can be captured up to 90%, but it may require substantial expenses. Accordingly, when assuming that expense is infinite, the efficiency will also be zero. Therefore, the distance between a point in the stormwater capture curve and a line connecting two points of each extreme case can be regarded as efficiency in accordance with capacity of NPS control detentions. In other word, it is an indicator which evaluates a cost-effectiveness of NPS control detentions and defines the distance between a point in a capture curve and a line connection two extreme points in a capture curve as efficiency. Accordingly, Fig. 8 shows the conceptual efficiency curves.

It can be noticed that the optimal capacity of NPS control detentions of the catchment would be a size that can capture stormwater of 2.3852 mm. That is, it seems most efficient to determine actual capacity of NPS control detentions by multiplying 2.3852 mm by the area of drainage. In this case, stormwater capture rate is 59.4%, meaning that 5.94 out of 10 stormwater events at the catchment can be captured by NPS control detentions, and the rest (4.06) can capture 2.3852 mm.

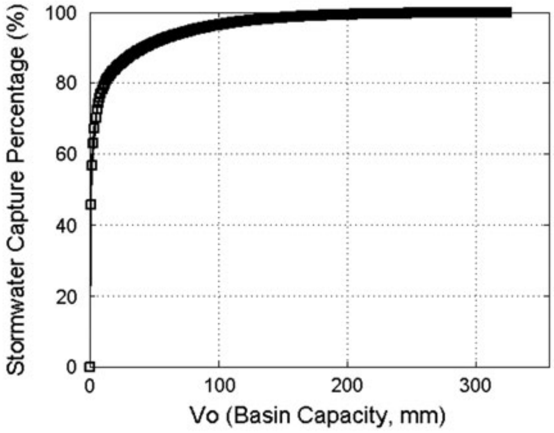

Fig. 6. Stormwater capture curve.

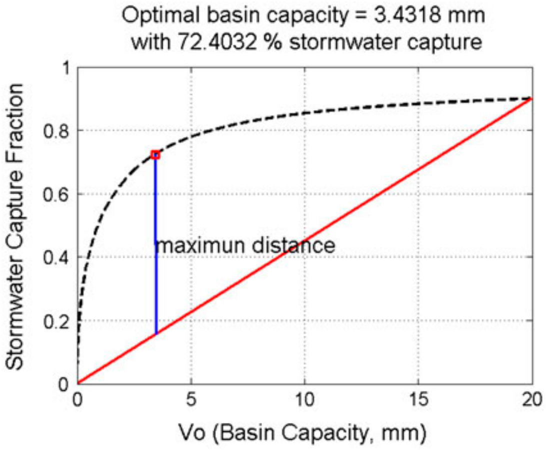

Fig. 7. Stormwater capture curve with conceptual efficiency line.

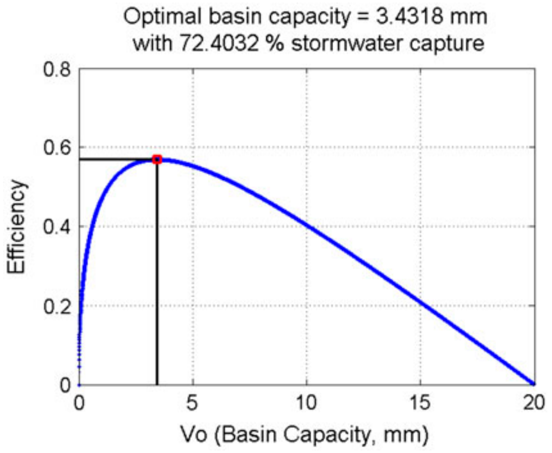

Fig. 8. Conceptual efficiency curve.

Using Eq. (7), annual average CN value in consideration of soil moisture condition can be calculated, and stormwater capture curve (Fig. 9) and conceptual efficiency curve (Fig. 10) can be created, then the optimal capacity of NPS control detentions can be determined (Bold line in blue of Fig. 10). In Figs. 9 and 10, all lines of Fig. 9 and all thin lines of Fig. 10 are drawn from all by grid cell data. When considering spatially heterogeneous characteristics and AMC of land surface, it seems most efficient to determine the optimal capacity of NPS control detentions by multiplying 3.2273 mm by the area of drainage, which is 6,640 m^3. In this case, stormwater capture rate is 56.61%, meaning that 5 or 6 events out of 10 stormwater events at the drainage catchment can be fully captured by NPS control detentions, and the rest (that is, 4 or 5 events) can capture only 3.2273 mm.

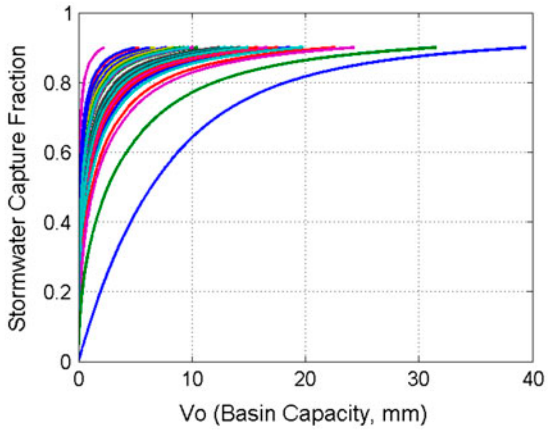

Fig. 9. Stormwater capture curves from all cells.

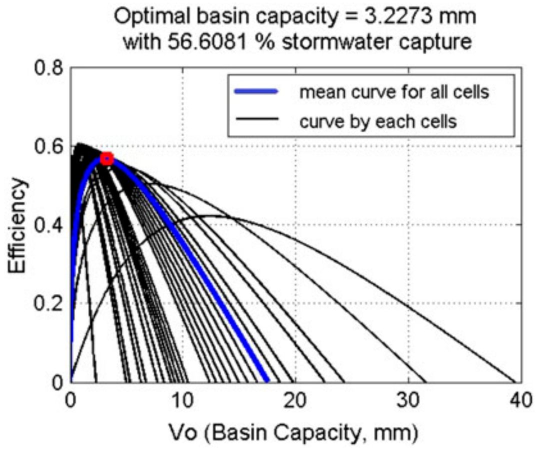

Fig. 10. Conceptual efficiency curves from all cells.

4. Conclusions

This study is purposed to improve two limitations of using the constant CN value when deriving stormwater capture curve (in considering of AMC and spatial heterogeneity of land surface) based on the research of Kim [1]. As the drainage catchment for this study, Jeungpyeong drainage catchment (205.75 ha) located in Korea was selected, and drainage catchment was divided into square-type grid cells of resolution by 30 m × 30 m in order to calculate CN value of each cell. Also, in a bid to figure out changes in CN values in accordance with AMC, rainfall record of Cheongju Branch of the Korea Meteorological Administration was used, and AMC were assigned by rainfall events. And then, the CN value was recalculated by cells. As a result, it is noticed that the optimal capacity of a NPS control detention is found out differently between the case of CN value with temporal and spatial average and the case of CN values with temporal and spatial variability. These results show that the impact of spatial and temporal variability of hydrologic conditions in the drainage catchment on determining the optimal capacity of a NPS control detention should be investigated. Compared with managing flood events, as for NPS management, small rainfall events are relatively more important, so that another management approach should be come up with. Since in case of an event with relatively smaller rainfall event, the amount of stormwater to be generated from the same rainfall depth can be substantially different in accordance with AMC, the temporal variability of hydrologic moisture conditions should be incorporated in designing a NPS control detention. Also, in accordance with land use characteristics, the loss rate of

NPS is very different, so that heterogeneous characteristics of land surface should be incorporated in designing a NPS control detention.

Acknowledgment

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