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APPROACH OF LAND COVER BASED ASYMPTOTIC CURVE NUMBER REGRESSION EQUATION TO ESTIMATE RUNOFF

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ABSTRACT

The Natural Resources Conservation Service-Curve Number (NRCS-CN) method has been used widely for estimation of direct runoff. However, the determination methods of CN values for land covers from the National Engineering Handbook Chapter 4 (NEH-4) are inadequate due to uncertainty raised in determining the of the hydrologic soil group, which could change from reported soil survey data due to soil compaction and other human activities. To overcome these drawbacks, an asymptotic CN (ACN) regression equation for the relationship between measured streamflow and rainfall for gauged river basins (ACN-RB) was developed and used in various studies. The ACN-RB determines various CN values depending on the amount of rainfall in an event. The ACN-RB has limitations in application to ungauged river basin because the ACN-based CN values do not consider various land covers. Accordingly, 13 land cover-based asymptotic CN regression equations (LC-ACN-REs) were developed and evaluated in this study by comparing estimated direct runoff with measured data. The estimated direct runoff using the LC-ACN-REs, which were classified as "standard types", matched observed direct runoff well, as evidenced by a Nash-Sutcliff efficiency (NSE) value of 0.78 for Jungrang A basin and a NSE value of 0.73 for Tancheon A basin. Copyright © 2016 John Wiley & Sons, Ltd.

KEY WORDS: asymptotic CN; direct runoff; LC-ACN-RE; NRCS-CN; NEH-4

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RÉSUMÉ

La méthode des curver numbers du service natural conservation des ressources (NRCS-CN) a été largement utilisée pour l'estimation de ruissellement direct. Cependant, les méthodes de détermination des valeurs de CN données par le manuel national de l'ingénierie (*National Engineering Handbook Chapitre 4* ; NEH-4) sont inadéquates en raison de l'incertitude dans la détermination du groupe hydrologique de sols ; cette classification est. de nature à évoluer en raison des tassements du sol et d'autres activités humaines. Afin de remédier à ces inconvénients, une équation de régression asymptotique du CN pour la relation entre le débit mesuré et les précipitations a été élaborée pour des bassins hydrographiques calibrés (ACN-RB) et utilisée dans diverses études. L'ACN-RB détermine différentes valeurs CN selon la quantité de précipitations au cours d'un épisode. L'ACN-RB a aussi ses limites dans l'application aux bassins non jaugés parce que ces valeurs CN ne considèrent pas la diversité des couvertures terrestres. En conséquence, les équations de régression (LC-ACN-RE) de treize couvertures terrestres ont été proposées et évaluées dans cette étude, en comparant le ruissellement direct estimé avec les données mesurées. Les ruissellements directs estimés, qui ont été proposés comme types standard, sont bien en accord avec les valeurs observées, comme en témoignent les coefficients de Nash-Sutcliff obtenus pour deux bassins, de 0,78 pour le bassin de Jungrang et de 0,73 pour le bassin de Tancheon. Copyright © 2016 John Wiley & Sons, Ltd.

MOTS CLÉS: CN asymptotique; ruissellement direct; LC-ACN-RE; NRCS-CN; NEH-4

INTRODUCTION

Hydrologic analysis is a pivotal component for determining effective rainfall, direct runoff, design floods, non-point source (NPS) pollution, and other water-related phenomena.

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Approche d'une équation de régression asymptotique des curve numbers basée sur l'occupation du sol pour estimer le ruissellement

Direct runoff is calculated based on meteorological (i.e., rainfall, evaporation, infiltration, surface storage, etc.) and geomorphological (i.e., land covers, soil textures, topography, etc.) factors. To date, various direct runoff estimation approaches (Moon *et al.*, 2014) have been developed and used such as the Φ-index (McCuen, 1989), the ω-index (Subramanya, 1994), the Natural Resources Conservation Service-Curve Number (NRCS-CN, Andrews, 1954) and Hydrograph Analysis (Subramanya, 1994), among others. The NRCS-CN method developed by Andrews (1954) calculates direct runoff using rainfall events. The United States Department of Agriculture extended the NRCS-CN method to consider the Antecedent Moisture Condition (AMC) in determining CN values (Soil Conservation Service (SCS), 1972) and suggested CN values corresponding to the combination of various land covers and soil hydraulic groups defined in the National Engineering Handbook Chapter 4 (NEH-4) (SCS, 1985).

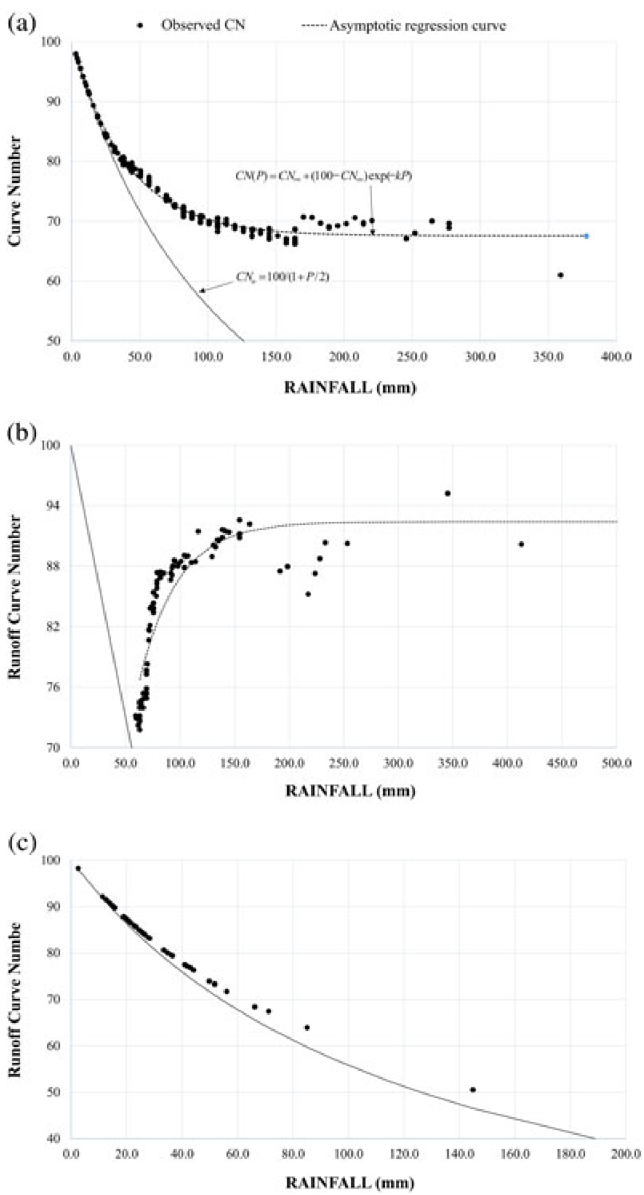

Figure 1. Three types of asymptotic CN regressions in the study by Hawkins (1993); CN(*P*) is the Curve Number as a function of rainfall and $CN_o = 100/(1 + P/2)$defines a threshold below which no runoff occurs until rainfall *P* in mm exceeds an initial abstraction of 20% of the maximum potential retention

The CN values included in the NEH-4 have been widely used in various spreadsheet-based runoff models (e.g., L-THIA (Harbor, 1994) and STEPL (Tetra Tech, 2011; Park *et al.*, 2014)) as well as in Geographic Information System (GIS)-based direct runoff and NPS pollution estimation models (Lim, *et al.*, 2005a; Tyagi *et al.*, 2008; Kim *et al.*, 2008; Soulis and Valiantzas, 2012; Park *et al.*, 2014; Tejram *et al.*, 2012).

However, the NRCS-CN method is limited in its ability to represent paddy and non-agricultural land uses (e.g., public and recreational land uses). In addition, the determination methods of CN values for land covers from the NEH-4 are inadequate due to uncertainty raised in considering the characteristics of hydrologic soil groups, which may change from those described by soil survey data due to soil compaction and other activities. To overcome these drawbacks,

Table I. Sites used to evaluate the curve number in South Korea

Name of land cover	Site	Area (m^2)	Monitoring period	Number of observations
Residential area	1	22,600	2011 ~ 2013	66
	2	11,970		
Manufacturing area	1	1,507	2008 ~ 2014	30
	2	381,000		
	3	12,000		
	4	13,000		
	5	1,770		
Commercial area	1	12,586	2008 ~ 2013	65
	2	10,384		
Regional public facility area	1	50,635	2011 ~ 2013	33
Recreational facility area	1	15,882	2010 ~ 2013	26
Road	1	12,400	2009 ~ 2012	25
	2	7,700		
Upland	1	16,998	2009 ~ 2012	38
	2	21,567		
Orchard	1	2,484	2010 ~ 2013	50
	2	864		
Green house	1	3,009	2008 ~ 2011	32
	2	4,029		
Paddy	1	136,900	2010 ~ 2012	41
	2	80,900		
Pasture	1	25,200	2009 ~ 2012	28
Forest	1	21,700	2008 ~ 2010	28
Bare land	1	17,213	2008 ~ 2013	67
	2	9,950		

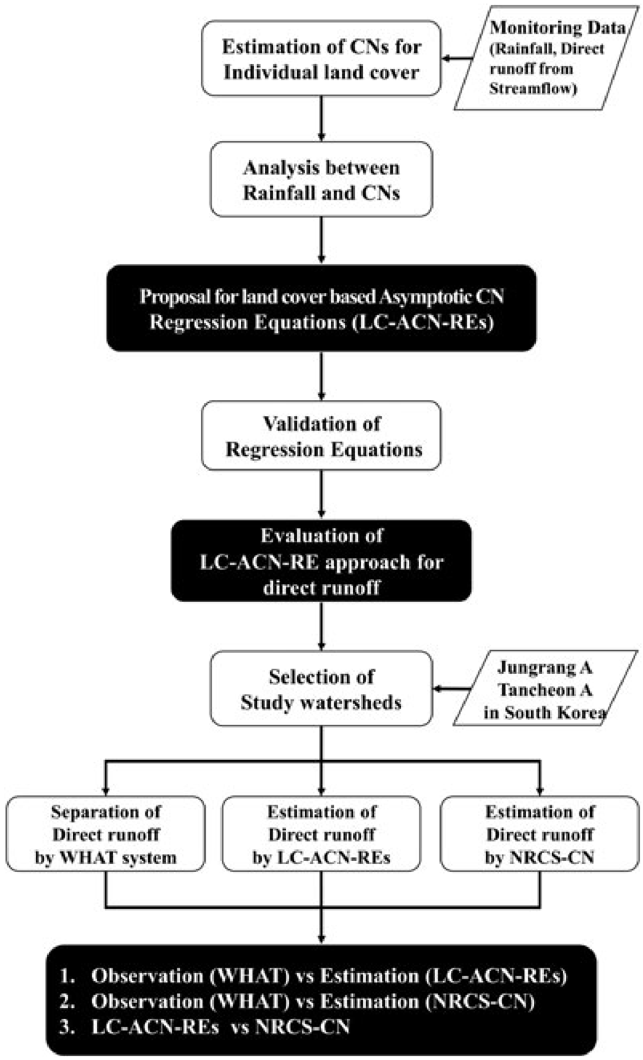

Figure 2. Research flow for development of LC-ACN-REs

Hawkins (1993) developed the asymptotic curve number (ACN) for river basin (ACN-RB) method that can determine CN values using historical rainfall data. The rainfall-CN relationship in the ACN-RB method can be classified as "Standard", "Violent", and "Complacent" types, and the Standard type is usually applicable to field sites. The Standard type assumes that the rainfall-CN relationship shows an asymptotic trend such that when there is an increase in rainfall, a decrease in CN value is observed, and this relationship can be expressed as an asymptotic regression.

The ACN-RB method derives various CN values that represent different rainfall amounts while the original SCS-CN (SCS, 1972, 1985) method uses only a single CN value from the NEH-4 or, at most, three different CN values corresponding to different AMC. Due to the flexible characteristics of the ACN-RB method compared with the conventional CN method, various studies using the ACN-RB method have been conducted, including those at small forest-dominated river basins in Georgia (Tedela *et al.*, 2008), New Hampshire (Tedela *et al.*, 2012), India (Gundalia and Dholakia, 2014) and Poland (Banasik and Woodward, 2010). These application studies showed that there is an asymptotic relationship between CN and rainfall amounts. Also, Kim *et al.* (2008) and Kwak *et al.* (2010) illustrated that direct runoff estimated using the ACN-RB method matched observed runoff better than estimates using the original NRCS-CN method did.

However, these ACN-RB studies were conducted using measured rainfall and streamflow data without consideration of various land covers in a river basin. Thus, the ACN-RB method developed by Hawkins (1993) has difficulties in estimating direct runoff in ungauged river basins due to the lack of rainfall-runoff records. In order to apply the ACN method and improve runoff estimation in an ungauged river basin where rainfall-runoff relationships are not available, the approaches that incorporate rainfall-runoff characteristics for each land cover type into CN estimation should be developed and validated.

Thus, the objectives of this research were two-fold: 1) to develop land cover-based asymptotic CN regression equations (LC-ACN-RE) using historical rainfall and runoff measurements for each land cover; 2) to evaluate the success of LC-ACN-REs in estimating direct runoff at ungauged river basins. The resulting LC-ACN-RE approach could contribute to alleviating the limitations of the original ACN-RB method and be useful for predicting direct runoff at ungauged basins.

MATERIALS AND METHODS

NRCS-CN method

The NRCS-CN method (Equation 1–3) was derived based on the empirical methods for separating direct runoff from rainfall (SCS, 1985).

$$P = I_a + F + Q \tag{1}$$

$$P = \frac{Q}{P\text{-}I_a} = \frac{F}{S} \tag{2}$$

$$I_a = \lambda S \tag{3}$$

where Q is the direct runoff (mm), P is the rainfall (mm), F is the amount of rainfall retained after runoff begins (mm), S is the potential maximum retention after runoff begins (mm), I_a is the initial abstraction (mm) including surface storage, interception, evaporation, infiltration, and λ is the initial loss factor.

By combining Equations 1 and 2, Equation 4 for expressing the relationship between direct runoff and rainfall can be derived,

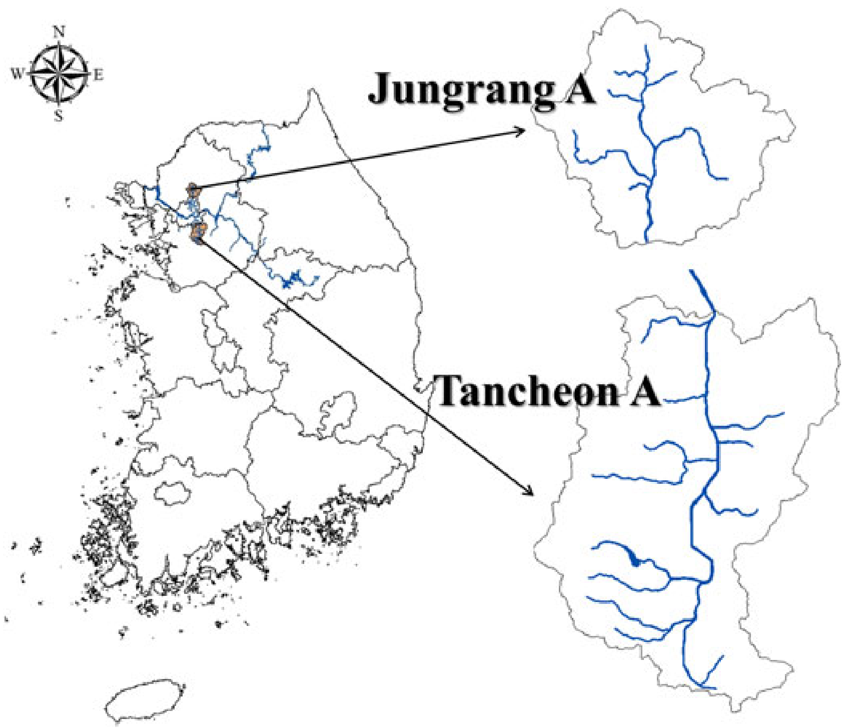

Figure 3. Study river basins in South Korea for evaluation of the LC-ACN-REs

$$Q = \frac{(P\text{-}I_a)^2}{(P\text{-}I_a + S)} \tag{4}$$

As I_a is approximated to 0.2S, direct runoff (Q) of Equation 4 can be expressed as Equation 5:

$$Q = \frac{(P\text{-}0.2S)^2}{(P + 0.8S)}, P \geq 0.2S \qquad Q = 0, P \leq 0.2S \tag{5}$$

Then, S can be defined with CN indicating runoff capacity of the river basin as shown in Equation 6.

$$S = \frac{25400}{CN}\text{-}254 \tag{6}$$

CN values for ungauged regions can be determined by considering critical factors such as soil hydraulic groups, hydrologic condition, land cover, and AMC.

Asymptotic CN regression for river basin (ACN-RB) method

The ACN-RB method suggested by Hawkins (1993) is used to analyse the relationship between CN and rainfall in various river basins in the United States. Specifically, after estimating CN values for individual rainfall events, the relationship between CN and rainfall is analysed. The processes of this method are as follows. In the first step, the rainfall and runoff depths must be sorted independently in the descending order. As matching between the ordered rainfall and runoff, the second step is the identification of CNs for the matched pairs by using Equations 7 and 8. The secondary relationship of rainfall and CN often emerges at this stage. Once this relationship between rainfall and CN is apparent, the asymptote can be defined in the third step.

$$S = 5\left[P + 2Q\text{-}\sqrt{4Q^2 + 5PQ}\right] \tag{7}$$

$$CN = 25400/254 + 5\left[P + 2Q\text{-}\sqrt{4Q^2 + 5PQ}\right] \tag{8}$$

The asymptote definition (Hawkins, 1993) can be classified into a "Standard", "Violent" or "Complacent" type (Figure 1). The CN value for the Standard type (Equation 9) decreases with the increasing rainfall amount and converges; in contrast, is converged while the CN value of the Violent type increases on the contrary to the Standard type. Hawkins (1993) showed that most river basins are included in the Standard type.

Standard:

$$CN(P) = CN_\infty + (100\text{-}CN_\infty)\exp(\text{-}kP) \tag{9}$$

Violent:

$$CN(P) = CN_\infty[1\text{-}\exp(\text{-}kP)] \tag{10}$$

where CN_∞ is the asymptotic CN value, P is the rainfall (mm), and k is the fitting constant.

Table II. Land cover of the Jungrang A and Tancheon A basins in South Korea for evaluation

Name of land cover	Area (km^2)	
	Jungrang A River Basin	Tancheon A River Basin
Residential area	9.18	25.91
Manufacturing area	1.13	3.01
Commercial area	3.41	5.73
Recreational facility area	0.03	0.59
Road	5.05	6.64
Regional public facility area	4.26	12.25
Paddy	4.49	4.59
Upland	6.94	16.33
Greenhouse	1.58	2.35
Orchard	0.34	0.13
Others	0.22	0.56
Deciduous forest	26.83	70.69
Coniferous forest	10.62	20.64
Mixed forest	32.39	16.28
Pasture	5.84	0.18
Golf course	0.00	1.38
Others	0.00	2.71
Inland wetland	0.00	1.21
Coastal wetland	0.00	0.00
Mining site	0.00	0.01
Bare land	5.02	10.18
Water	0.83	2.50
Sea water	0.00	0.00
Total	118.16	203.87

Monitoring site

The Ministry of Environment in South Korea (Guem River Watershed Management Committee (GRWMC), 2014; Han River Watershed Management Committee (HRWMC), 2014; Youngsan River Watershed Management Committee (YRWMC), 2014; Nakdong River Watershed Management Committee (NRWMC), 2014) has conducted extensive monitoring projects nationwide to estimate NPS runoff and pollution (unit loadings) from individual single land cover areas across the country over the last eight years (Table I). Through these long-term monitoring projects, the long-term NPS pollutant discharges based on rainfall and direct runoff were obtained.

Monitoring of residential and manufacturing areas was conducted from 2011 to 2013. In total, 13 single land cover areas including agricultural (upland, orchard, greenhouse and paddy), urban (residential area, manufacturing area, regional public facility area, recreational facility area and roads), forest, pasture and bare land. The residential site 1 was comprised of individual houses (22,600 m^2) while the residential site 2 had ten apartment buildings (11,970 m^2). These residential areas had respective separate sewer systems, and the direct runoff data were collected by measuring

Table III. Parameters of the LC-ACN-REs and the quality of estimated CN-observed CN fit

Name of land cover	CN_∞ (Asymptotic CN)	100-CN_∞	k (Fitting constant)	R^2
Residential area	82.2	17.8	0.0095	0.70
Manufacturing area	71.1	28.9	0.0102	0.57
Regional public facility area	59.2	40.8	0.0167	0.90
Recreational facility area	84.8	15.2	0.0427	0.89
Road	66.3	33.7	0.0110	0.74
Commercial area	92.0	8.0	0.0185	0.90
Upland	43.3	56.7	0.0077	0.75
Orchard	63.7	36.3	0.0176	0.82
Green house	54.1	45.9	0.0077	0.57
Paddy	72.3	27.7	0.0233	0.50
Pasture	23.0	77.0	0.0191	0.99
Forest	52.9	47.1	0.0274	0.53
Bare land	74.8	25.2	0.0200	0.76

Note: CN_∞ and k are used in standard type ACN regression equation $CN(P) = CN_\infty + (100 - CN_\infty)\exp(-kP)$

66 runoff events caused by rainfall ranging from 1 mm to 509 mm. In the manufacturing area, the direct runoff data were monitored at five sites from 2008 to 2014. The manufacturing sites 1 to 5 comprised of an automobile repair factory (381,000 m^2), a semiconductor plant and industrial machine manufacturing plant (381,000 m^2), an industrial complex of rural area (12,000 m^2), a steel manufacturing plant (13,000 m^2), and areas of an automobile parts manufacturing plant (1,770 m^2), respectively. The monitoring of the commercial area was conducted from 2008 to 2012. The commercial site 1 (12,586 m^2) was comprised of low density restaurants while the commercial site 2 (10,384 m^2) had a high density of offices and parking lots. Monitoring of direct runoff at a sewage treatment plant for the regional public facility area (50,635 m^2) was conducted from 2010 to 2013 and monitoring of a public park (15,882 m^2) was conducted from 2011 to 2013. For road areas, monitoring was conducted from 2009 to 2012. The

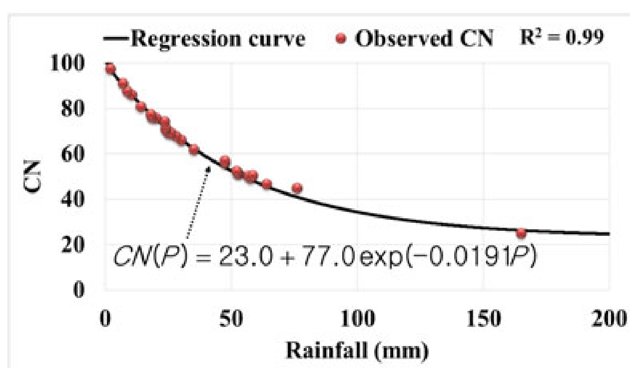

Figure 4. Relationship of the observed CN and rainfall for pasture; CN(P) is the curve number as a function of rainfall volume

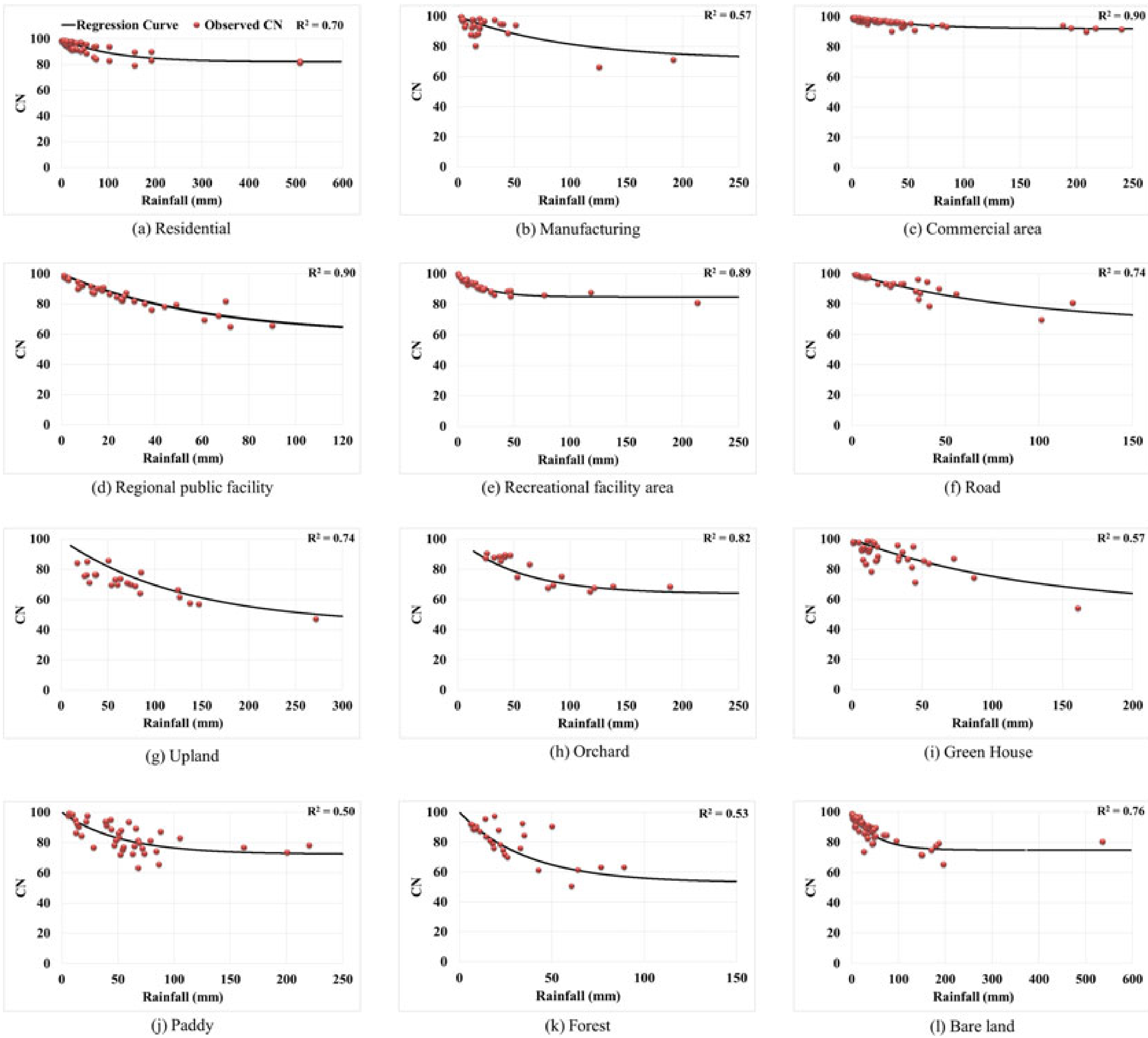

Figure 5. Relationship of the observed CN and rainfall for individual land cover

road sites 1 and 2 on four-lane roads were selected for monitoring the direct runoff data. The road site 1 had a length of 330 m and width of 37.5 m (12,400 m^2) while road site 2 (7,700 m^2) had a length of 240 m and width of 32.1 m.

The upland monitoring location was comprised of sites 1 and 2 with potato (16,998 m^2) and other crops (21,567 m^2) such as balloon flower root, potato, Chinese cabbage, Codonopsis lanceolate (DeoDeok in Korean), which were monitored from 2009 to 2012. The direct runoff at these sites did not occur when a rainfall event was 10 mm or less. Two sites in orchard areas were monitored for direct runoff from 2010 to 2013. The orchard site 1 had pear cultivation (2,484m^2), and orchard site 2 had apple cultivation (864 m^2). Direct runoff at the orchards was not generated if a rainfall event was 10 mm or less. Two sites of greenhouses for tomato cultivation having areas of 2,009 m^2 (greenhouse site 1, 5 houses) and 4,029 m^2 (greenhouse site 2, 6 houses) were also monitored from 2008 to 2011. Paddy and pasture areas also had two sites each that were monitored from 2010 to 2012. The areas of paddy sites 1 and 2 were 136,900 m^2 and 80,900 m^2, respectively, and those for the pastures were 25,200 m^2 and 21,700 m^2, respectively. A bare land area was monitored for direct runoff from 2008 to 2013 at two sites; both sites 1 and 2 were located in elementary

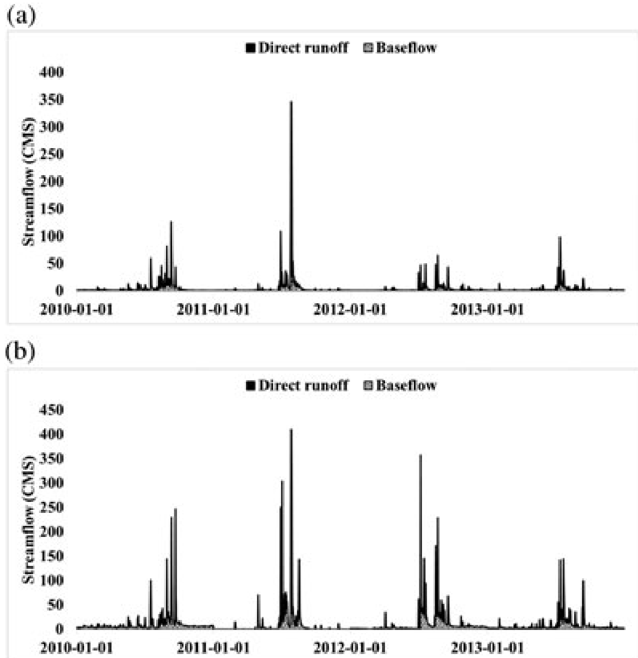

Figure 6. Separated direct runoff and baseflow using the “WHAT” system at two river basins

school areas comprised of a sandy soil having areas of 17, 213 m^2 and 80,900 m^2, respectively.

Development of land cover-based of asymptotic CN regression equations

Direct runoff monitoring data at the 25 monitoring locations just described were used in this study to derive the LC-ACN-REs. In this regard, the observed rainfall and the monitored direct runoff for the 13 land cover types were used in Equation 7 in order to estimate the CN values for each rainfall event. Then the event-based relationships between rainfall and CN were developed as mathematical equations by regression analysis.

After regression analysis, the types of asymptote could be defined as Standard, Violent or Complacent. In the case of Standard and Violent types, the equations were built with a form of asymptotic regressions. The asymptotic CN regression of the Standard type suggested in this study is shown in Equation 9 and the asymptotic CN regression of the Violent type is shown in Equation 10. However, the relationship between rainfall and CN defined as the Standard asymptotic CN regression was determined to be suitable for all land covers considered in this study.

Finally the validity of LC-ACN-REs was assessed by the correlation between estimated CNs from LC-ACN-REs and measured CN as reflected by the coefficient of determination (R^2).

Table IV. Observed (using the “WHAT” system) and predicted 4-year average direct runoff (excluding days of no rainfall events) by NRCS-CN and LC-ACN-REs, including quality of estimates

River basin	Year	WHAT system	NRCS-CN			LC-ACN-REs		
		Direct runoff (m^3/s)	Direct runoff (m^3/s)	R^2	NSE	Direct runoff (m^3/s)	R^2	NSE
Jungrang A	2010	5.29	1.75	0.48	0.34	4.82	0.52	0.51
	2011	9.64	5.69	0.89	0.83	8.36	0.90	0.84
	2012	4.13	2.59	0.78	0.73	5.68	0.85	0.77
	2013	3.50	1.41	0.63	0.58	4.02	0.71	0.70
	Total	5.52	2.73	0.80	0.76	5.60	0.82	0.78
Tancheon A	2010	7.43	1.95	0.81	0.47	7.69	0.73	0.65
	2011	10.04	4.27	0.69	0.51	13.33	0.82	0.81
	2012	9.84	7.28	0.71	0.58	12.61	0.72	0.77
	2013	5.86	1.01	0.53	0.23	6.98	0.60	0.58
	Total	8.20	4.27	0.57	0.55	9.97	0.72	0.73

NSE = Nash-Sutcliff Efficiency

Evaluation of the LC-ACN-RE

The evaluation of the developed LC-ACN-REs was conducted at two study river basins (Jungrang A and Tancheon A) included in the Korean Total Maximum Daily Load (TMDL). Then, daily direct runoff data from 2010 to 2013 were extracted from observed flow data of the two river basins using the “WHAT” system (Lim *et al.*, 2005b, 2010), after which the extracted direct runoff values were compared with the estimated runoff obtained from LC-ACN-REs (Figure 2).

The areas of Jungrang A and Tancheon A river basins are 118.16 km^2 and 203.87 km^2, respectively, and both river basins are the headwaters of a larger drainage basin (Figure 3). The land cover distribution of the Jungrang A river basin is comprised of forest (59.1%), urban (19.5%), agricultural (11.5%), pasture (4.9%), and bare land (4.3%). Likewise, the Tancheon A river basin is covered by forest (52.6%), urban (26.6%), agricultural (11.9%), pasture (2.1%), and bare land (5%) (Table II). The 2007 land cover map at 30-m resolution, provided by the Environmental and Geographical Information System, composed of Landsat TM and Korea Multi-Purpose Satellite-2 (KOMPSAT 2) images, was used in this study. Mining sites and other classifications of land use in agricultural areas that were not considered in the LC-ACN-RE approach were reclassified as bare land and upland, respectively; similarly land uses such as golf courses and others dominated by grass were reclassified as pasture.

Direct runoff estimated by the proposed LC-ACN-REs was compared with observed direct runoff for evaluation of the LC-ACN-RE approach. Due to the lack of data for observed direct runoff in most river basins, direct runoff and baseflow were separated from observed daily streamflow. For this, 8-day interval streamflow data at the mouth of the

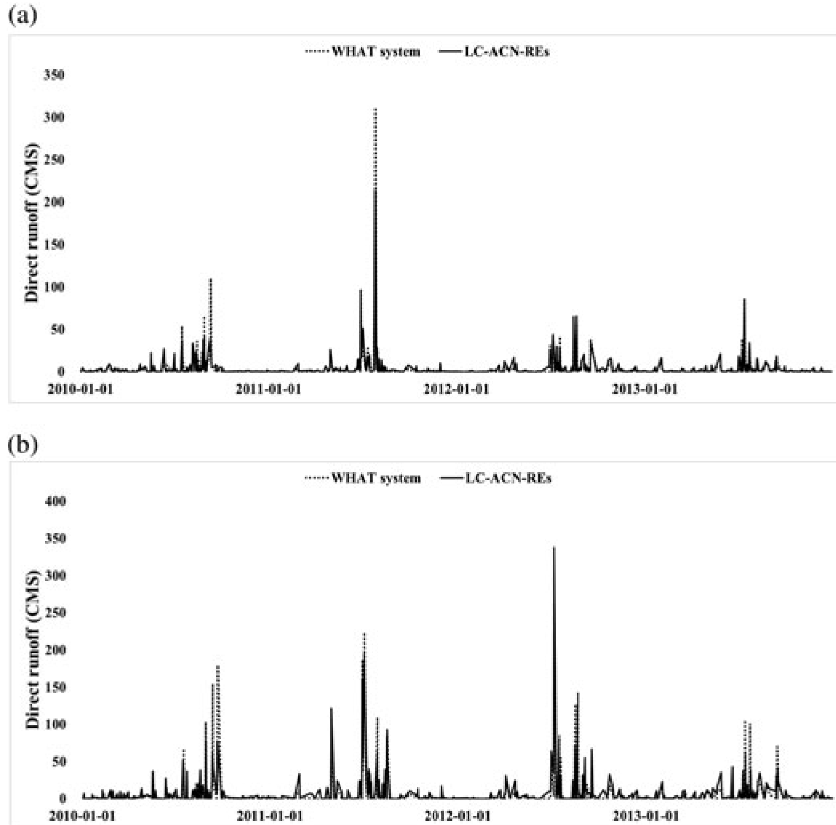

Figure 7. Comparisons between estimated direct runoff by LC-ACN-REs and direct runoff separated from observed streamflow using the "WHAT" system (2010 ~ 2013)

two study river basins were expanded to continuous daily streamflow from 2010 to 2013 using the daily streamflow extension regression methods proposed by Park *et al.* (2012). Direct runoff separation was conducted using the web-based "WHAT" system (Lim *et al.*, 2005b, 2010), one of the most widely used direct runoff/baseflow models. The detailed description of the WHAT system is available in Lim *et al.* (2005b).

Also, the LC-ACN-REs were compared with the NRCS-CN method for estimation of direct runoff. Using the NRCS-CN method, CNs for two study river basins (having same types of land cover and soil) were selected based on the NEH-4, after which a representative CN of each river basin was calculated on the basis of area-weighted averages. The daily runoff was estimated by applying the calculated representative CNs to Equation 5.

RESULTS AND DISCUSSION

Results of 13 LC-ACN-REs

The results of the 13 LC-ACN-REs are shown in Table III, and compared with measured CN values (Figures 4 and 5). Also, all of the developed 13 LC-ACN-REs were found to be Standard types, compatible with the results in the study by Hawkins (1993).

Similar to the ACN-RB method (Hawkins, 1993), the LC-ACN-REs developed in this study also showed that the estimated CN values were dynamically changed by rainfall amount, and that an asymptotic CN value could be attained as the amount of rainfall increased. In addition, the estimated CN values became larger as rainfall decreased. Particularly for rainfall events of less than 10 mm, the estimated CN values were greater than 90 in most land cover types except those for uplands and orchards. This result might be caused by the value for S (potential maximum retention after runoff begins), which is largely affected by high runoff occurring from high rainfall events (Kim *et al.*, 2008; Kwak *et al.*, 2010).

However, CNs in the NRCS-CN method are not dynamically changed as the magnitude of rainfall changes. Thus, in the NRCS-CN method, estimation of direct runoff in low-rainfall events can be very much less than that predicted by the LC-ACN-REs. For example, in the case of the pasture, the NEH-4 in the NRCS-CN method provides CN values ranging from 38 to 78 depending on the hydrologic soil group. However, in the present study, CN values greater than 90 were observed among CN values estimated by the LC-ACN-REs for low rainfall events (Figure 4).

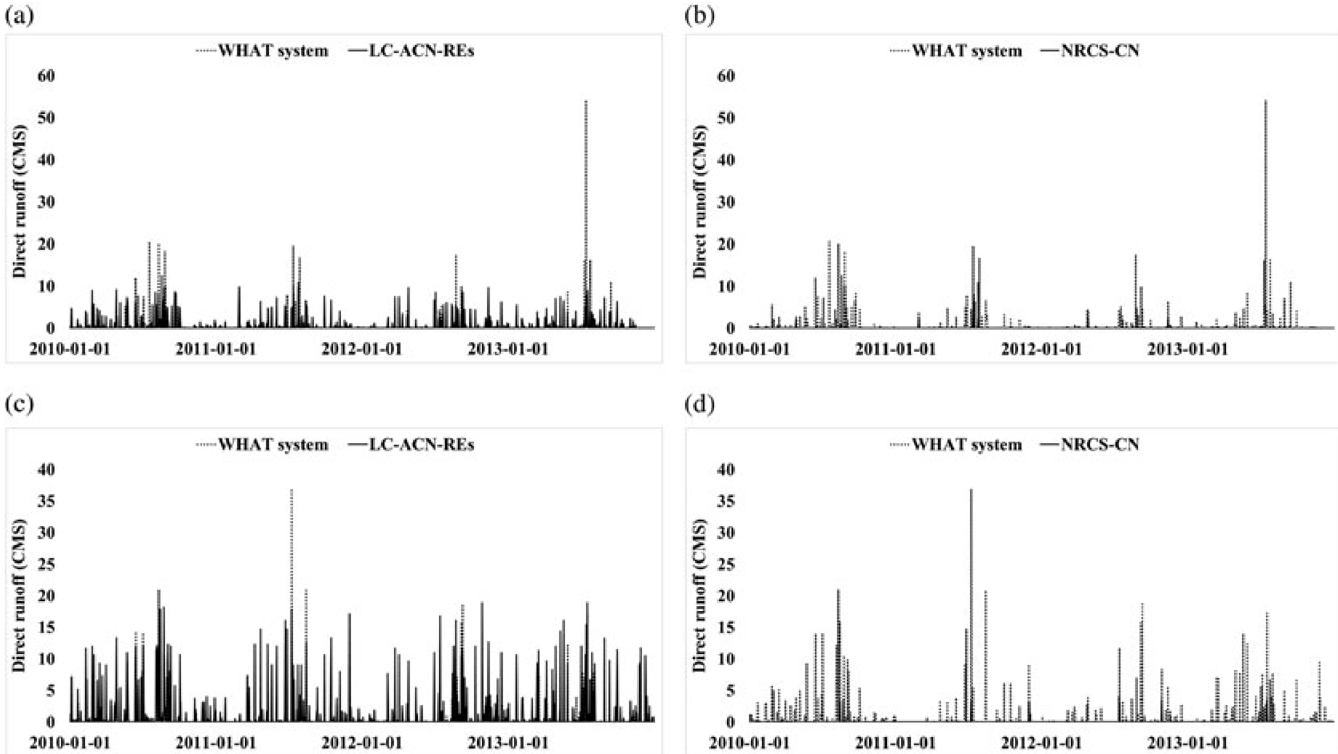

Figure 8. Comparison between estimated direct runoff using NRCS-CN and LC-ACN-REs methods and separated direct runoff from observed streamflow using the "WHAT" system for rainfall amount of 30 mm or less

Also, the asymptotic CN values estimated from the LC-ACN-REs ranged from 23.0 to 92.0. Here, most asymptotic CN values were greater in urban areas than in agricultural areas (Table III). Specifically, among all land cover types, the CN value was the greatest for commercial areas and the lowest for pasture. High CN values in an urban area might be the result of low rainfall storage capacity due to impervious area and compacted soil.

For validation of the LC-ACN-REs, the coefficient of determination (R^2) was calculated between the estimated and the measured direct runoff. Generally, a R^2 value greater than 0.50 for a regression equation is considered acceptable to describe hydrologic phenomena (Santhi *et al.*, 2001; Van Liew *et al.*, 2007). All R^2 calculated in the present study were greater than 0.5 for all land cover types. The minimum and the maximum R^2 were achieved in the paddy land cover ($R^2 = 0.50$) and in the pasture land cover ($R^2 = 0.99$), respectively. Thus, the proposed LC-ACN-REs can be appropriately selected according to the types of land cover and applied for the estimation of direct runoff.

Evaluation of LC-ACN-RE approach for direct runoff in two river basins

The direct runoff estimated using the WHAT system to analyse streamflow (from 2010 to 2013) in the Jungrang A and Tancheon A river basins is shown in Figure 6. As a result, the estimated 4-year average direct runoff (including days of no rainfall events) was 2.48 m^3/s in Jungrang A (average streamflow of 5.33 m^3/s) and 4.97 m^3/s in Tancheon A (average streamflow of 14.0 m^3/s). Thus, the ratio of direct runoff to streamflow was 47% in Jungrang A and 36% in Tancheon A, indicating that the streamflow in both river basins was dominated by baseflow rather than by direct runoff.

The estimated direct runoff using the developed LC-ACN-REs was 5.60 m^3/s in Jungrang A and 9.97 m^3/s in Tancheon A. Compared with the observed direct runoff determined using the WHAT system, the 4-year average results from the LC-ACN-REs (excluding days of no rainfall events) were not significantly different. The differences in estimates using the two approaches was only 0.08 m^3/s (R^2 of 0.52–0.90 and NSE of 0.51–0.84) in the Jungrang A basin and 1.77 m^3/s (R^2 of 0.60–0.82 and NSE of 0.58–0.81) in the Tancheon A river basin (Table IV and Figure 7). According to Ramanarayanan *et al.* (1997) and Moriasi *et al.* (2007), the acceptable NSE and R^2 criteria ensuring satisfactory calibration of stream flow models are NSE ≥ 0.5 and $R^2 \geq 0.5$. Based on these criteria, the performance of the LC-ACN-REs developed in the present study was acceptable in both study river basins for all compared years (Table IV).

Using the NRCS-CN method, the estimated 4-year average direct runoff was 2.73 m^3/s (R^2 of 0.48–0.89 and NSE of 0.34–0.83) in Jungrang A and 4.27 m^3/s (R^2 of 0.53–0.81 and NSE of 0.23–0.58) in Tancheon A. Thus, the NRCS-CN method led to the lower R^2 and NSE than the approach of LC-ACN-REs, and not all R^2 and NSE for direct runoff estimated by the NRCS-CN method met the acceptability criteria (NSE $\geq$ 0.5 and $R^2 \geq 0.5$), as shown in Table IV. Furthermore, the 4-year average direct runoff estimated using the NRCS-CN had significant differences (more than 50% difference overall, and more than 95% difference for rainfall events of 30 mm or less) between the observations and the estimations in both study river basins (Table IV, Figure 8). In this regard, the NRCS-CN method cannot reflect the effect of low rainfall on estimation of direct runoff due to its reliance on a single CN value in Equation 4 ($Q = 0$, $P \leq 0.2S$) regardless of rainfall amount. Thus, direct runoff calculated using the NRCS-CN method is much less than that estimated using the LC-ACN-REs.

>Regarding these results, the LC-ACN-RE approach was expected to predict more accurate direct runoff in practice than the NRCS-CN method. Furthermore, the LC-ACN-RE approach could extend the applicability and availability of estimates of direct runoff for ungauged river basins because these equations were based on individual land cover types.

CONCLUSIONS

In this study, 13 LC-ACN-REs were developed and validated using widely accepted criteria. The equations were evaluated by individually estimating the direct runoff at two river basins considering individual land cover type and comparing these estimates against observed runoff. All 13 LC-ACN-REs were found to be "Standard" types according to Hawkins' (1993) classification. Based on the validated results (with R^2 of 0.50–0.99), most of the LC-ACN-REs produced CN values that were highly correlated with the CN values determined using measured data.

The LC-ACN-RE approach was used to estimate direct runoff from 2010 to 2013 in two river basins (Jungrang A and Tancheon A). For the evaluation, estimated direct runoff values from the LC-ACN-REs were compared with observed direct runoff extracted using the WHAT system. The comparison showed high correlations between estimated and observed direct runoff in both the Jungrang A basin ($0.84 > \text{NSE} > 0.51$) and the Tancheon A basin ($0.77 > \text{NSE} > 0.50$). In contrast, the traditional NRCS-CN method produced low correlations between the estimated runoff and observed runoff in the basins. Thus, the LC-ACN-RE approach produced equations that can predict direct runoff more accurately than the NRCS-CN method.

The 13 LC-ACN-REs developed in this study overcome disadvantages of the Hawkins's ACN-RB method (Hawkins, 1993) for application of the asymptotic curve-number method at ungauged river basins. Also, simply considering the dynamic variation of the CN values for the regression between rainfall and CN values, the LC-ACN-RE approach will be useful for accurately estimating direct runoff in a river basin. Accordingly, the LC-ACN-RE approach will make significant improvements in not only the estimation of direct runoff, but also in estimating NPS pollution in medium- and long-term plans for river basin management, such as TMDLs management.

In the near future, the LC-ACN-RE approach will be integrated with a GIS and Web-GIS-based prediction system for easy application of the procedure. In addition, river basin characteristics such as river basin slope, baseflow contribution, and channel routing need to be incorporated for application of the LC-ACN-RE approach in large river basins.

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