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Development of a Precipitation-Area Curve for Warning Criteria of Short-Duration Flash Flood

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Abstract. This paper presents quantitative criteria for flash flood warning that can be used to rapidly assess flash flood occurrence based on only rainfall estimates. This study was conducted for 200 small mountainous sub-catchments of the Han River basin in South Korea because South Korea has recently suffered many flash flood events with short duration. Flash Flood Guidance (FFG) was defined as the depth of rainfall of a given duration required to cause minor flooding at the outlet of a small stream basin and was estimated using threshold runoff (TR) and antecedent soil moisture conditions in all the sub-basins. The soil moisture conditions were estimated during the flooding season, i.e., July, August and September, over 7 years (2002~2009) using the Sejong University Rainfall Runoff (SURR) model. A ROC analysis was used to obtain optimum rainfall values and a generalized precipitation-area curve (P-A curve) was developed for flash flood warning thresholds. The threshold function was derived as P-A curve due to the reason that the precipitation threshold with short duration is highly related to basin area than any other variables. Generalized thresholds for flash flood warning were obtained for rainfall rates of 42, 32 and 20 mm/h in sub-basins with areas of 22~40 km^2, 40~100 km^2 and >100 km^2, respectively. The proposed P-A curve was validated based on actual flash flood events in different sub-basins, which showed the viability of the proposed criteria to capture actual flash floods using only the rainfall rate and area of a sub-basin. The key advantage of this method is possible to issue flash flood warnings without the need to run entire hydro-meteorological model chains in the region where the short-duration flash flood frequently occurred.

1 Introduction

Flash floods are among the deadliest natural disasters, with significant socioeconomic effects and the highest average mortality rate among different types of floods (Jonkman, 2005). Flash floods are generally associated with localized, intense rainfall events in small and medium watersheds. There are some difficulties in managing flash flood control due to the unusually short response time among the nature disasters. Additionally, the climate change has increased the number of extreme rainfall events and the risk of flash floods (Gregory and Mitchell, 1995; Palmer and Raisanen, 2002). Therefore, the technology of reliable flash flood forecasting model is necessary for flash flood response.

For deciding flash flood occurrence, there are three methods which are the flash flood susceptibility assessment, flow comparison method, and rainfall comparison method (Hapuarachchi et al., 2011). The flash flood susceptibility assessment can be considered as a useful first step in determining the contributing factors to flash flood vulnerability of a catchment using limited data (Collier and Fox, 2003). The flow comparison method is to compare the model-driven flow value with the observed flooding threshold which is a criterion for deciding whether flooding should be expected or not. However, this approach has some limitations for real-time flash flood forecasting because it requires long historical data and hydrological simulation to establish the observed frequency distribution. The rainfall comparison method compares threshold rainfall causing flooding flow to the forecast rainfall instead of comparing forecast flow with flooding flow. This method is an eminent tool to warn of an imminent flash flood and the typical method is FFG (Flash Flood Guidance) concept (Carpenter et al., 1999; Carpenter and Georgakakos, 1993). This method is commonly used for flash flood forecasting as it is easily understood by the general public.

However, some recent studies suggested the limitations of FFG (Norbiato et al., 2008; Montesarchio et al., 2011; Hapuarachchi et al., 2011). The limitations of FFG are in the assumptions of spatially/temporally uniform rainfall and linear responses, and the use of regional relationships to make inferences abut ungauged locations. FFG performance in ungauged bains is less accurate (Norbiato et al., 2008). The recent studies tried to improve the warning accuracy. Schmidt et al. (2007) proposed a raster-based method to derive a gridded FFG (GFFG). Miao et al. (2016) established a strategy for flash flood warning that is based on the definition of rainfall threshold using distributed hydrological model.

South Korea has recently suffered many flash flood events in the mountainous regions. More than 64% of South Korea is mountainous and prone to flash floods with very short rainfall durations. Recent heavy rainfalls in South Korea have triggered flash floods and landslides that caused severe damage to infrastructure and resulted in dozens of deaths. Notably, heavy rainfall events have resulted in several flash floods since 2000, such as events in 2005, 2006, 2008 and 2012 in Geyonggi-do, Gangwon Inje, Gyeongsanbuk-do, and Gangwon Hoengseong, respectively. Especially, the hourly maximum rainfall exceeded 50mm/hr and 60 mm/hr in 2006 and 2011, most of the flash flood events were caused by short rainfall duration of less than one hour.

It is less important to exquisitely estimate the soil moisture or runoff in the regions where the flash flood occur frequently with short rainfall duration because flash floods do not wait the warning of flash flood forecasting system. It is necessary to develop the criteria for deciding intuitively the flash flood occurrence with short duration. Although FFG-based methods provide useful mechanisms for flash flood warning, the real-time estimates of soil moisture required in some regions are often challenging to acquire prior to rapid response against flash floods. In this study, we proposed quantitative criteria using P-A curve for flash flood warning based on FFG. Also, this study derives the importance of soil moisture estimation and which variable has the largest effect for deciding flash floods related to topography information. The proposed criteria and methodology will serve as an important tool for issuing flash flood warnings based on only rainfall information.

2 Methods

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2.1 QPC Computation

Figure 1 presents the overall procedure used to evaluate the quantitative precipitation criteria (QPC) for flash flood warning. To obtain FFG at current time (t) which is a summation of threshold runoff (TR) and soil moisture deficit, TR at each sub-basin is estimated. And, the soil moisture conditions from actual rainfalls are simulated by using SURR model. And then we can decide whether flash flood at certain basin is occurred or not by comparing this FFG value and 1-hr time ahead actual rainfall.

To obtain the QPC for flash flood warning, a virtual rainfall (VR) of 1~100 mm/h with a 1 mm/h increment is used for comparison with observed rainfall (OR). The occurrence criteria for virtual flash floods (e.g., VR > FFG or VR < FFG) and occurrence criteria for actual flash floods (e.g., OR > FFG or OR < FFG) are used to obtain ROC scores for rainfall rates of 1~100 mm/h in each sub-basin, as presented in Table 1. The rainfall values that produce the maximum ROC score are selected in each sub-basin. Finally, a generalized precipitation–area curve (P-A curve) is obtained using selected rainfall rates that produce maximum ROC scores as a function of the relevant area of each basin.

2.2 Flash Flood Guidance

FFG is defined as the depth of rainfall of a given duration needed to cause minor flooding at the outlet of a small stream basin. It is generally estimated for 1-, 3-, and 6-hour durations. The method used to compute FFG is the opposite of that of a rainfall-runoff model, in which runoff is the desired result. In FFG, a specific amount of rain is required to produce a given amount of runoff based on estimates of current soil moisture conditions, which are derived from soil moisture models. Two quantitative products are needed to compute FFG: 1) threshold runoff and 2) rainfall-runoff curves.

The threshold runoff value represents the amount of runoff, or rainfall excess, over a given duration tr required to induce flooding in small streams. Assuming that catchments respond linearly to excess rainfall, threshold runoff (R) can be estimated by equating the peak catchment runoff determined from the catchment unit hydrograph over a given duration to the streamflow at the basin outlet associated with flooding. This is expressed mathematically as follows:

$$Q_p = q_{pR}RA \qquad \text{or} \qquad R = \frac{Q_p}{q_{pR}A} \tag{1}$$

where Q_p is the flood flow (cms or cfs), q_{pR} is the unit hydrograph peak for a specific duration tr, A is the catchment area (km^2 or mi^2) and R is the threshold runoff (cm or inches).

The flood flow Q_p can be defined either physically as bankfull discharge Q_{bf} or statistically as the two-year return period flow, Q_2. In this study, the bankfull discharge was computed from channel geometry and roughness characteristics using Manning's formula for steady, uniform flow (Chow et al., 1988):

$$Q_{bf} = B_b D_b^{5/3} S_c^{0.5}/n \tag{2}$$

where Bb is the channel width at bankfull (m), D_b is the hydraulic depth at bankfull (m), S_c is the local channel slope (dimensionless), n is the Manning's roughness coefficient and Q_{bf} is the bankfull flow (cms).

To obtain the peak catchment runoff, the unit hydrograph can be derived using various methods, such as Snyder's synthetic unit hydrograph approach (Chow et al., 1988) or the geomorphologic instantaneous unit hydrograph (GIUH) method (Rodríguez-Iturbe et al., 1979). In this study, we used the GIUH method to obtain peak catchment runoff.

To derive the rainfall-runoff curve, which represents current soil conditions, it is necessary to estimate soil moisture. Soil moisture data are obtained via direct measurements with tensiometers or indirect methods such as rainfall-runoff models. In this study, the Sejong University Rainfall Runoff (SURR) model was used to estimate soil moisture. This model was developed based on the storage function model (SFM) (Kimura, 1961) and improved hydrological components such as potential evapotranspiration, surface flow, lateral flow, and groundwater flow based on the physical properties of these components (Bae and Lee, 2011). Moreover, this model uses estimates soil moisture continuously to determine time-dependent soil moisture conditions. The soil profile is separated into adsorbed water, tension water, and free water components. The soil water characteristics that distinguish these water components include the wilting point, field capacity, and saturated soil moisture conditions. The free water component in the soil profile contributes to lateral flow and percolation, while the tension water component contributes to actual evapotranspiration. Eq. (3) represents the soil water variations and hydrological component changes based on precipitation and potential evapotranspiration changes:

$$\frac{dSW(t)}{dt} = P(t) - AET(t) - Q_{sur}(t) - Q_{lat}(t) - Q_{gw}(t) \qquad (3)$$

where $SW(t)$ is the soil water content (mm), $\mathrm{P}(t)$ is the mean areal precipitation (mm) and $AET(t)$ is actual evapotranspiration (mm). $Q_{sur}(t)$, $Q_{lat}(t)$ and $Q_{gw}(t)$ denote the runoff components of surface flow (mm), lateral flow (mm), and groundwater flow (mm), respectively. More detailed mathematical descriptions of the components were provided by Bae and Lee (2011).

2.3 Receiver Operating Characteristics (ROC)

The Receiver Operating Characteristics (ROC) approach, or the ROC curve method, was originally proposed to analyze the classification accuracy associated with differentiating signals from noise in radar detection. This type of analysis is now widely used in several domains to assess the performance of statistical models that classify values into one of two categories. A ROC curve plots the hit rate (HR) against the false alarm rate (FAR), which is computed using Eq. (4) and (5) and a contingency table or confusion matrix, as presented in Table 1.

$$Hit\ rate\ (HR) = \frac{H}{H+M} \qquad (4)$$

$$False\ alarm\ rate\ (FAR) = \frac{F}{F+N} \qquad (5)$$

Several contingency tables can be obtained based on varying decision thresholds associated with dichotomous events. The resulting point pairs (FAR, HR) from the contingency tables are plotted and connected by line segments. Additionally, they are connected to the point (0, 0), which corresponds to never forecasting the event, and to the point (1, 1), which corresponds to always forecasting the event. The perfect forecast yields values of FAR=0 and HR=1, i.e., the ROC curve consists of two line segments that coincide with the left boundary and upper boundary of the ROC diagram. At the other extreme of performance forecasting, random forecasts based on sampled climatological probabilities can exhibit FAR = HR, and the ROC curve consists of a 45-degree diagonal line connecting the points (0, 0) and (1, 1). ROC curves associated with real forecasts generally fall between these two extremes and plot above and to the left of the 45-degree diagonal. ROC curves that plot near the upper-left corner of the ROC diagram reflect better discrimination performance. Additionally, the area under a ROC curve can be used to summarize a ROC diagram, with the value of 1 representing a perfect forecast and 0.5 a random forecast.

3 Study Area and Datasets

The study was conducted in small mountainous sub-catchments in the Han River basin. The Han River basin is located in the center of the Korean Peninsula at 36°30´~38°55´N and 126°24´~ 129°02´E. The watershed area spans over 26,356 km², or approximately 23% of the South Korea territory (Figure 2). The 660 sub-basins with areas of 0.1~ 179.8 km² were delineated using ArcGIS (as shown in Figure 3a). Figure 3b shows the relative frequency of sub-basins with areas in different ranges. The average area of a sub-basin was 38.5 km², with a standard deviation of 25.7 km². Most of the sub-basins were ranged from 20~40 km², with a relative frequency of approximately 40%. The reservoirs located in the Han River basin were identified and omitted from further analysis to remove the effect of surface runoff storage on threshold runoff. The reservoirs store surface runoff from the upstream area and reduce the contributing area for surface runoff at downstream locations. Among the 660 sub-basins, 200 sub-basins (as shown in Figure 4a) were selected by filtering and removing the sub-basins with large areas. Figure 4b shows the relative frequencies of the areas of the selected sub-basins. The average area of a selected basin was 43.1 km², with a standard deviation of 19.8 km².

Rainfall and soil moisture were the main datasets used to estimate Flash Flood Guidance. Rainfall data were obtained at 96 locations from the Ministry of Land, Infrastructure and Transport (MOLIT) and at 25 locations from the Korean Meteorological Administration (KMA). A Digital Elevation Model (DEM) with a 30×30 m resolution and soil maps at a scale of 1:25,000 were obtained from the Water Resources Management Information System (WAMIS) of South Korea. The soil moisture conditions were estimated using the SURR hydrologic rainfall-runoff model.

In addition to the observed weather and flow datasets, data were collected for actual flash flood events. The actual flash flood information was obtained through different sources, including print and electronic media, over an 8-year period (2005–2012). Table 2 presents the locations, dates, times and maximum rainfall intensities of flash flood events in the Han River basin. Flash floods are common in the study area and occur almost every year. Notably, multiple flash flood events occurred in 2011.

4 Results and Analysis

4.1 Regional regression relationships based on channel geometry

Threshold runoff values are based on the flood flow Q_P, unit hydrograph peak q_{pR} and catchment area A. The bankfull flow Q_{bf} is used as flood flow in this study. The calculations of Q_{bf} and q_{pr} require the channel cross-section parameters. Direct measurements of channel cross-sections, which are performed through local surveys, are not possible on a continuous spatial scale. Therefore, regional regression relationships are established between channel cross-section properties and the geometric characteristics of the upstream catchment to obtain cross-sectional information for un-surveyed streams. These regression relationships are established using stream survey data. The dataset includes bankfull width (B), hydraulic depth (H), and local channel slope (S_c) from on-site measurements. These data were collected at 46 locations. Initially, the relationships between these parameters and the catchment area (A) were investigated using a power regression equation as follows:

$$X = \alpha A^{\beta} \tag{6}$$

where X represents B, H or S_c and parameters α and β are determined by the regression of X on A. Then, additional parameters such as stream length (L) and average basin slope (S) were investigated and included in the regression equation. The regression relationship can then be expressed as follows:

$$X = \alpha A^{\beta} L^{\gamma} S^{\delta} \tag{7}$$

where α, β, γ and δ are regression coefficients. A correlation analysis was performed to analyze the relationship between the parameters (B, H, and S_c) and basin characteristics (A, L and S). As shown in Table 3, the bankfull width B was positively correlated with the catchment area A but exhibited a significant negative correlation with the average basin slope S. Conversely, the hydraulic depth H was negatively correlated with A but positively correlated with L and S. The local channel slope S_c was negatively correlated with A and L. The derived regression equations are also shown in Table 3, and the determination coefficients of the regression equation were 0.76, 0.37 and 0.53.

4.2 Threshold runoff and FFG

Threshold runoff values were computed for effective rainfall durations of 1-hour in the 200 selected sub-basins. Figure 5(a) and (b) shows the estimated threshold runoff and its relative frequency in different ranges, respectively. Overall, the threshold runoff ranged from 18.7~42.8 mm/h with a mean of 31.8 mm/h. Additionally, a large number of basins had threshold runoff values of 25~30 mm/h and 35~40 mm/h.

Figure 6 presents the soil moisture contents and deficits simulated using a continuous rainfall-runoff model, SURR, during the flooding season, i.e., July, August and September, from 2002 to 2009 for four selected sub-basins. In each figure, the upper blue line represents the change in the soil moisture content based on the precipitation amount, while the grey dots represent the soil moisture deficit below saturation. The total soil moisture varied by sub-basin based on the soil conditions and basin characteristics. The soil moisture values were approximately 100-150 mm, 110 mm, 150 mm, 120 mm, and 105 mm in the Myungji, Soohang, Sanasa and Danjigol valleys, respectively. The soil moisture deficit generally ranged from 0~50 mm but was approximately 0~5 mm during 42% of the entire flood period. These values represent near-saturated soil conditions.

The mean area precipitation (MAP), estimated threshold runoff (TR) and FFG values for actual flash flood events that occurred in 2005, 2006, 2007 and 2009 in the Myungji, Soohang, Sanasa and Danjigol valleys, respectively, are presented in Figure 7. As shown in each figure, the values and trends of FFG, which is the sum of TR and the soil moisture deficit, are different at different locations. The values at Soohang valley and Sanasa valley are constant and indicate that the soil is already saturated due to antecedent precipitation, while the values at Myungji valley and Danjigol valley vary as precipitation inputs affect the soil moisture deficit. The time of flash flood occurrence was estimated based on when the hourly MAP exceeded the 1-hr FFG. Therefore, the time of flash flood occurrence was 0200 UTC on 3 August 2005 in the Myungji valley (32 mm MAP), 1300 UTC on 15 July 2006 in Soohang valley (66 mm MAP), 1600 UTC on 9 August 2007 in Sanasa valley (42 mm MAP) and 0600 UTC on 12 July 2009 in Danjigol valley (27 mm MAP). As shown in Table 2 and Figure 7, the times of flash flood occurrence computed from the FFG model exhibited satisfactory agreement with those from the observed flash flood record.

4.3 Quantitative Threshold of Flash Flood Guidance

Figure 8 shows the ROC scores of the four selected sub-basins estimated against virtual rainfall values of 1-100 mm/h with an interval of 1 mm/h. The virtual rainfall value associated with the peak ROC score was selected as the optimum rainfall. As expected, the minimum ROC score was 0.50, which represents random forecasting, while the maximum score and corresponding virtual rainfall were 0.90 and 32 mm/h in basin number 165, 0.91 and 30 mm/h in basin number 200, 0.87 and 22 mm/h in basin number 293, and 0.90 and 33 mm/h in basin number 442.

Similarly, the maximum ROC scores and corresponding optimum rainfall values were obtained in all other sub-basins. Figure 9 shows the ROC scores of all 200 sub-basins based on optimum rainfall values. The results show that the optimum rainfall values for flash flood warning criteria fall between 19 and 44 mm/h, with ROC scores of 0.85~0.98. An analysis of the selected optimum values and corresponding sub-basin areas revealed that the flash flood warning threshold could be best represented as a function of sub-basin area, as shown in Figure 10. Eq. (8) is a regression equation of a P-A curve that represents whether a flash flood will occur based on a given rainfall intensity and basin area:

$$P = 85.02 - 14.39 ln(A) \tag{8}$$

where A is the sub-basin area (km^2) and P is the hourly precipitation intensity (mm/h) that represent the quantitative flash flood criteria (QFFC). Thus, a flash flood will occur in a sub-basin with area A if the rainfall intensity exceeds the P-A curve;

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however, a flash flood will not occur if the rainfall intensity is below the curve. Note that the 1-hr precipitation intensity required to cause a flash flood decreases as a function of A.

In general, the P-A curve shows that a rainfall rate higher than 42 mm/h may trigger a flash flood in any sub-basin in the study area with an area greater than 22 km^2. We can further suggest the information of flash flood threshold based on fieldwork in different sub-basins to refine the flash flood criteria. Flash flood warning thresholds were established for rainfall rates of 42 mm/h, 32 mm/h and 20 mm/h in sub-basins with areas greater than 20 km2, between 40 and 100 km^2, and greater than 100 km2, respectively.

4.4 Validation

The proposed QFFC obtained from the P-A curve were validated for four actual flash flood events observed in the Myungji, Soohang, Sanasa and Danjigol valleys in 2005, 2006, 2007 and 2009. Figure 11 shows the 1-hr MAP and 1-hr QFFC in the selected sub-basins with different areas. The estimated values of 1-hr QFFC were 31.9 mm, 37.2 mm, 37.7 mm and 31.7 mm for sub-basins area of 40.1 km2, 27.8 km2, 26.8 km2, and 40.6 km2, respectively. The 1-hr MAP exceeded the 1-hr QFFC during the first three actual events, but the 1-hr MAP at Danjigol valley in 2009 event did not exceed the 1-hr QFFC due to differences in the rainfall pattern and characteristics, as the precipitation distribution at Danjigol valley was continuous with double peaks, while those of other events were short periods with single peaks. Therefore, the flash flood occurrence at Danjigol valley was the effect of 3-hr cumulative rainfall rather than 1-hr rainfall. Thus, the flash flood occurred because the 3-hr maximum MAP (70.4 mm) was greater than the 3-hr FFG (67.5 mm).

In addition, the flash flood occurrence was captured for 9 out of 12 events when the QFFC were validated. This result suggests that the proposed QFFC derived from the P-A curve captured the flash flood occurrence effectively in each sub-basin; however, further development is required for 3-hr and 6-hr QFFC in the near future.

5 Conclusion

In this study, quantitative criteria for flash flood warning were developed and assessed for sub-basins of the Han River in South Korea. Flash flood guidance based on threshold runoff was estimated for 200 sub-basins. The optimum rainfall values were obtained for each sub-basin by comparing FFG, virtual rainfall and observed rainfall values using a ROC analysis. The optimal rainfall values for the flash flood warning threshold were between 19 and 44 mm/h, with a ROC score of 0.85–0.98. The flash flood warning threshold can be best represented as a function of sub-basin area. A generalized precipitation–area curve of $P = 85.02 - 14.39\, ln(A)$ was proposed to the Han River basin in South Korea. The results showed that the optimum threshold for flash flood warning in a sub-basin could be effectively estimated as a function of the corresponding sub-basin area.

The key advantage of this method is possible to issue flash flood warnings without the need to run entire hydro-meteorological model chains in the region where the short-duration flash floods are frequently occurred. However, flash flood with more than 2-hr duration maybe sensitive to the soil moisture condition, and have response time. Therefore, the development of the coupled flash flood forecasting system which is divided with short and long-duration is necessary for managing flash flood efficiently.

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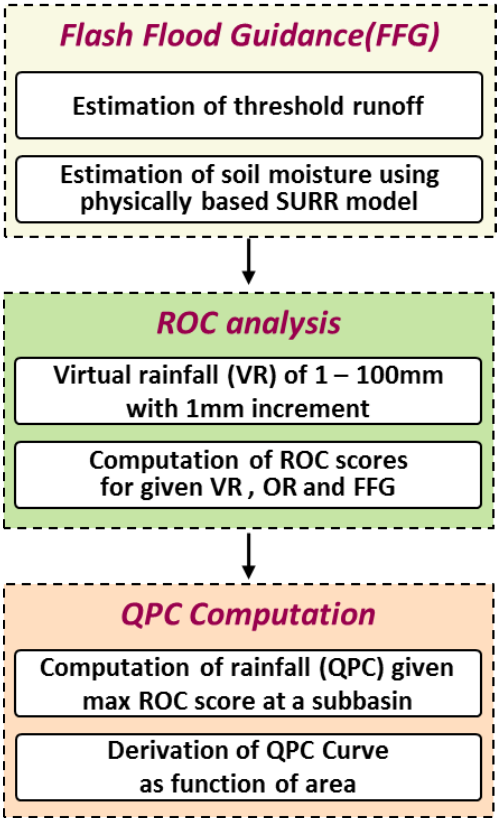

Figure 1: Overall methodology used to estimate the quantitative precipitation criteria.

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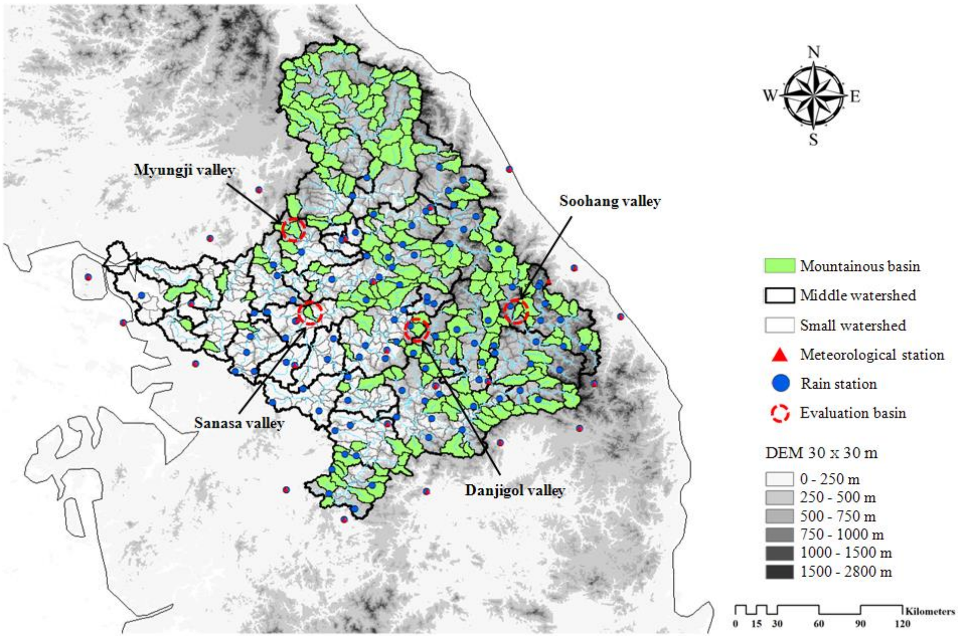
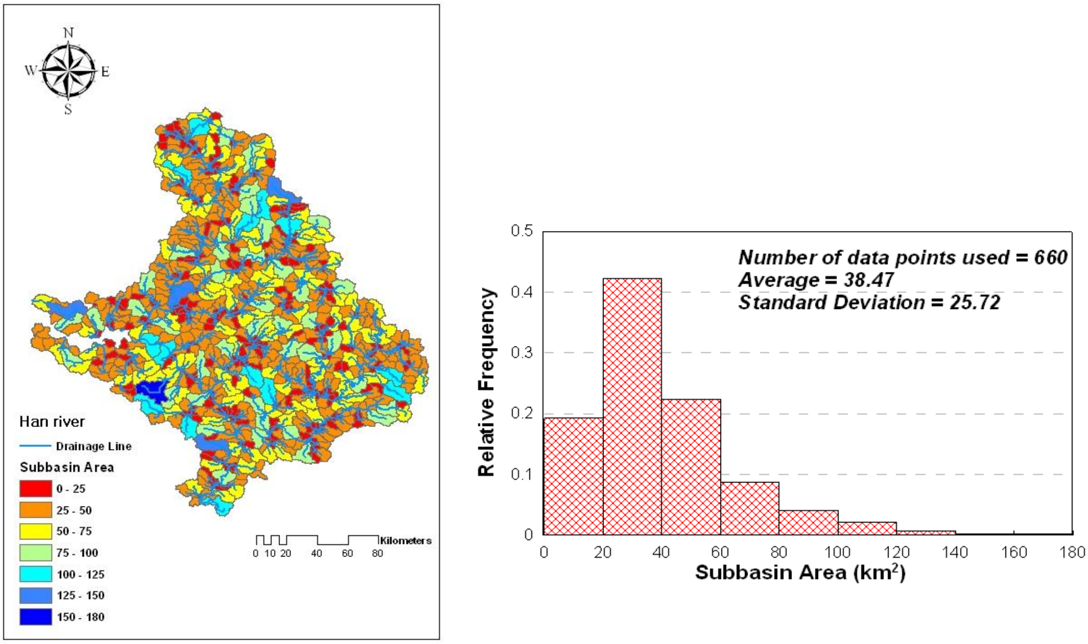
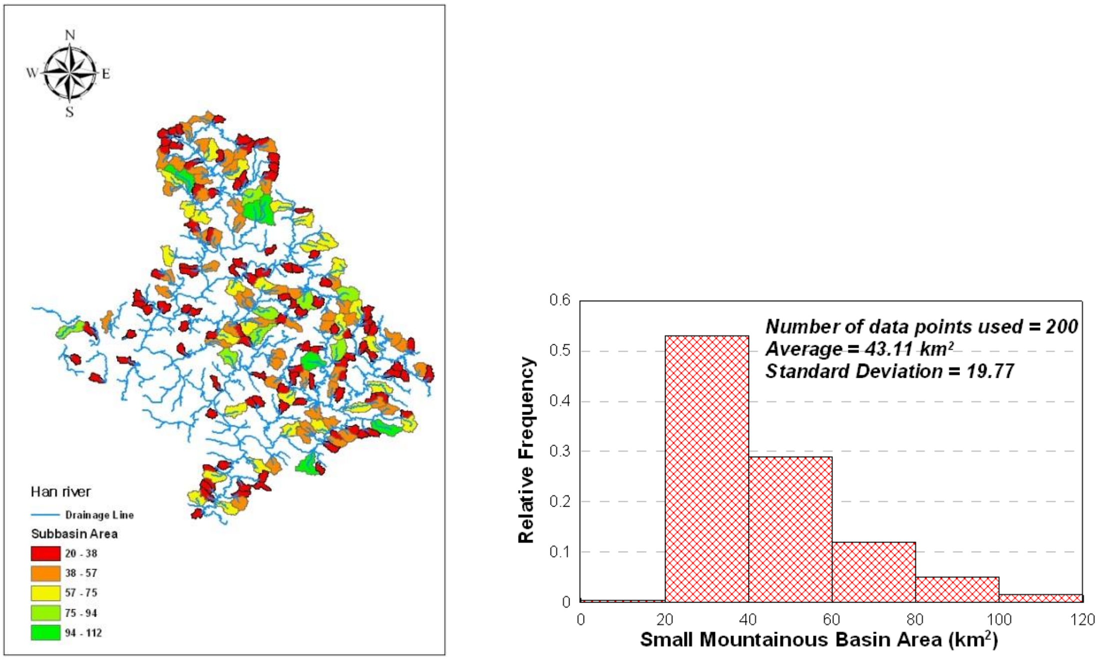


Figure 2: Study area.



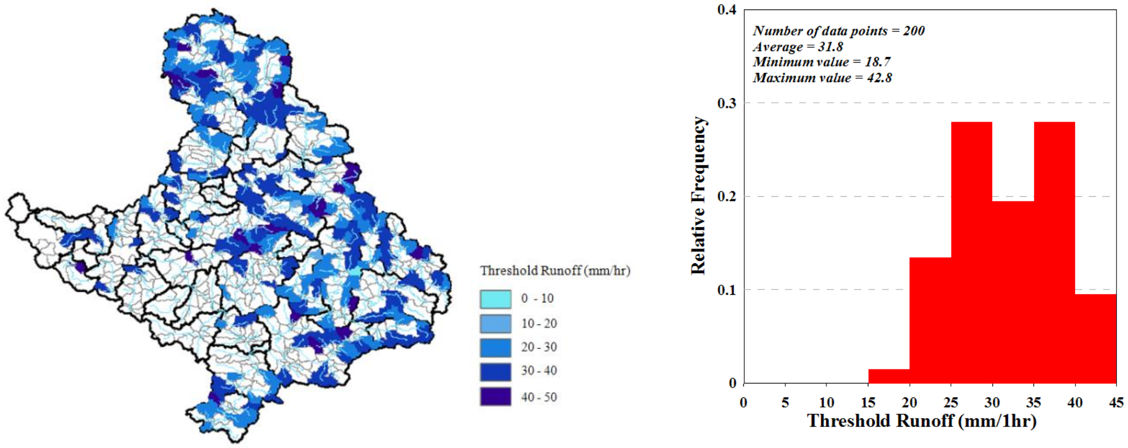
(a) **(b)**

Figure 3: (a) 660 sub-basins in the Han River basin and (b) their relative frequency of their areas.



(a) **(b)**

Figure 4: Selected 200 sub-basins in the Han River basin and (b) the relative frequency of their areas.



(a) (b)

Figure 5: (a) Threshold runoff and (b) the relative frequency of runoff.

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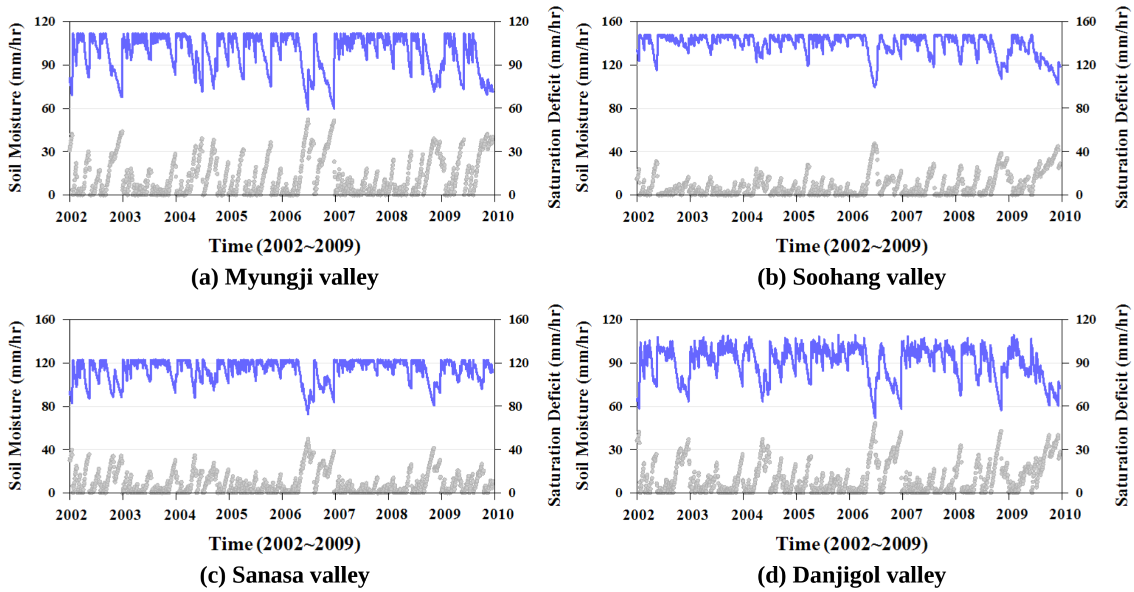
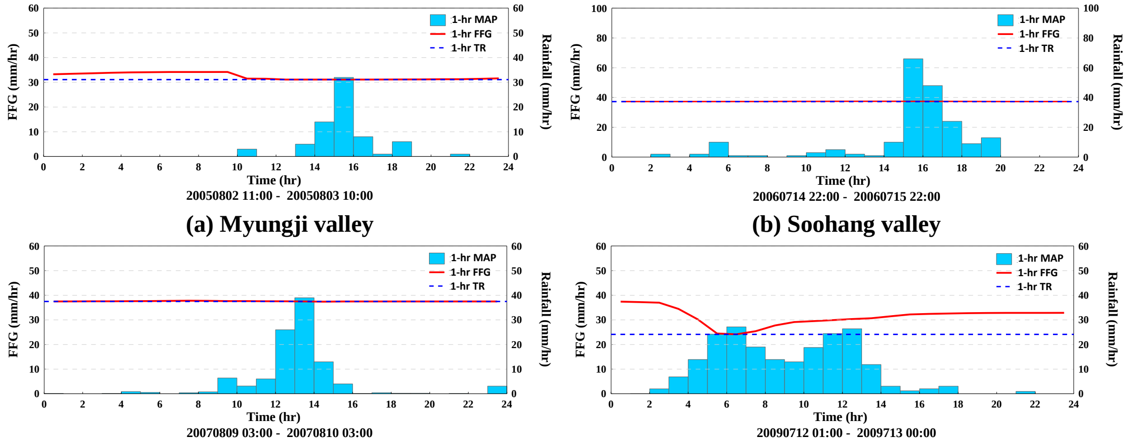


Figure 6: Soil moisture and soil moisture deficit in selected sub-basins.



(a) Myungji valley **(b) Soohang valley**

(c) Sanasa valley **(d) Danjigol valley**

Figure 7: Mean areal precipitation (MAP) and estimated FFG for selected flash flood events.

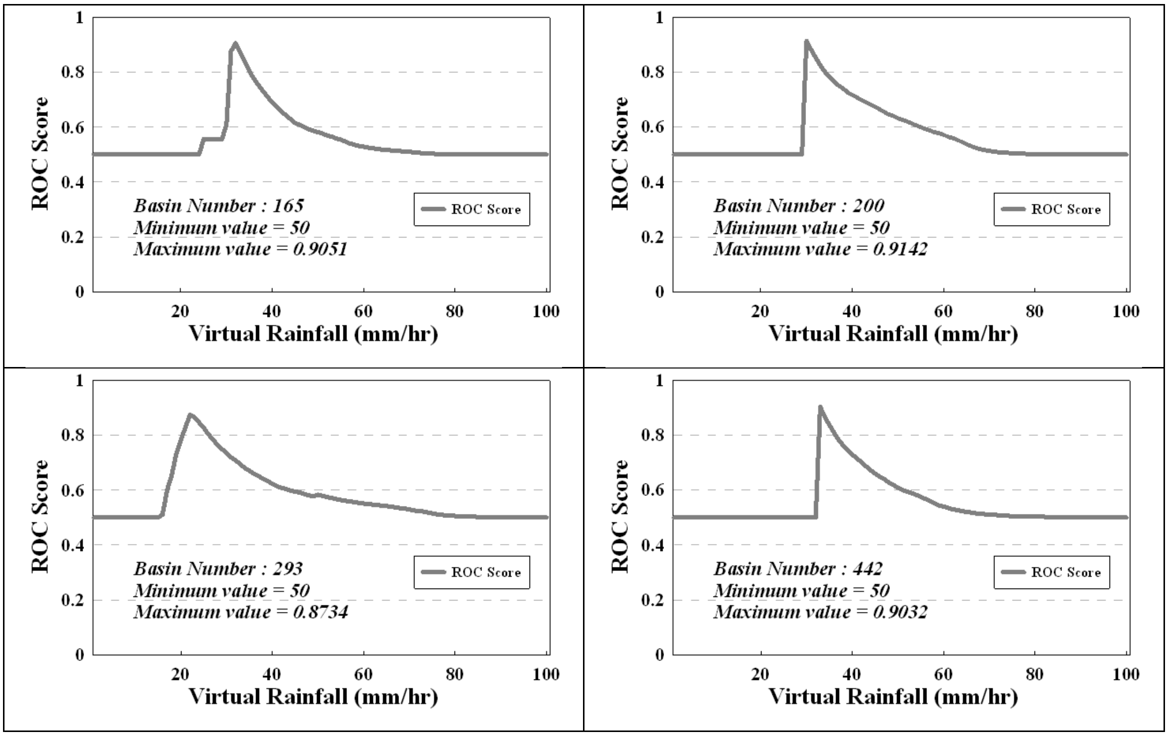


Figure 8: ROC score estimated for selected sub-basins using virtual rainfalls of 1–100 mm/h.

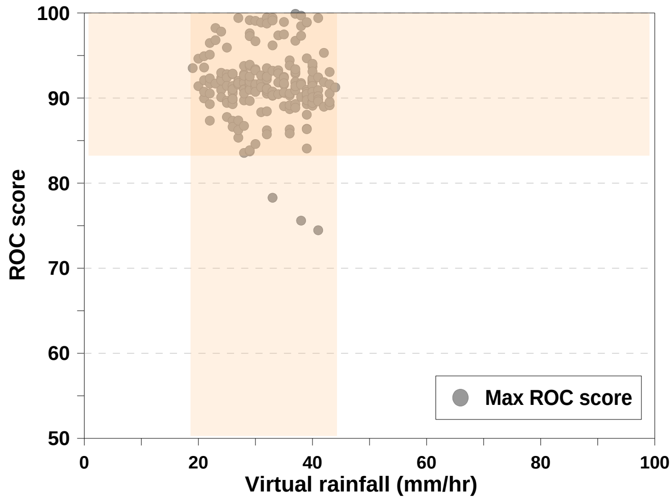


Figure 9: Relationship between maximum ROC and uniform virtual rainfall for all the sub-basins.

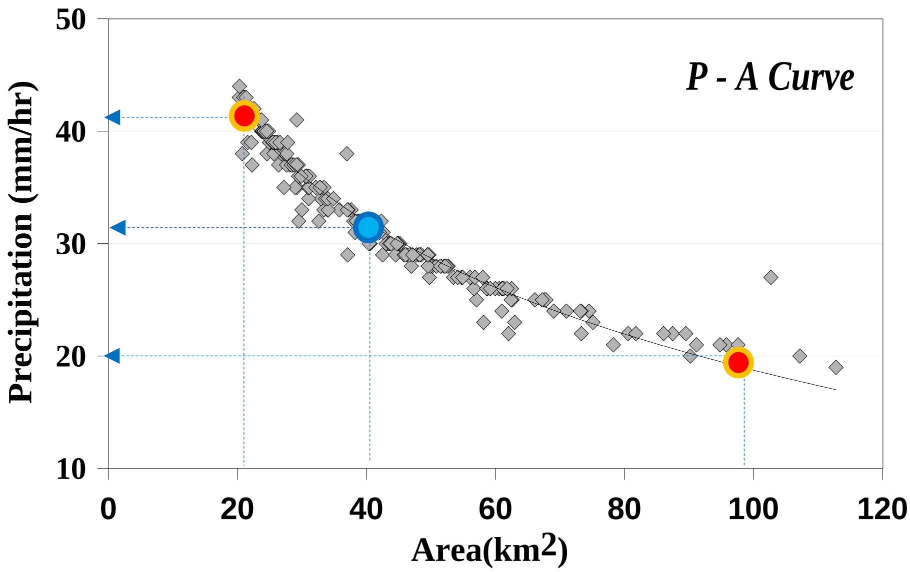


Figure 10: Derived QPC curve for quantitative flash flood conditions (QFFC).

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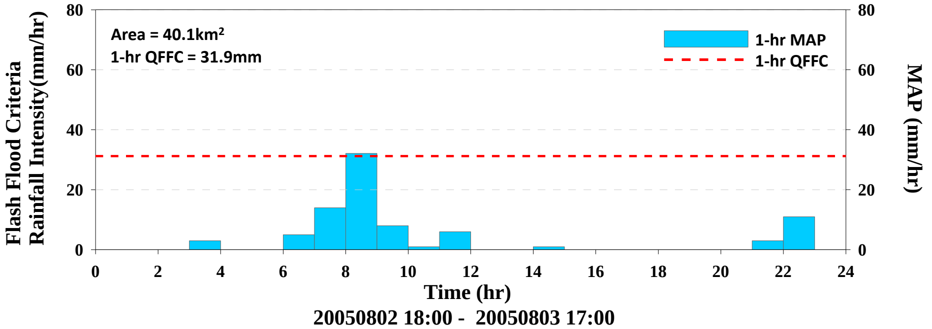
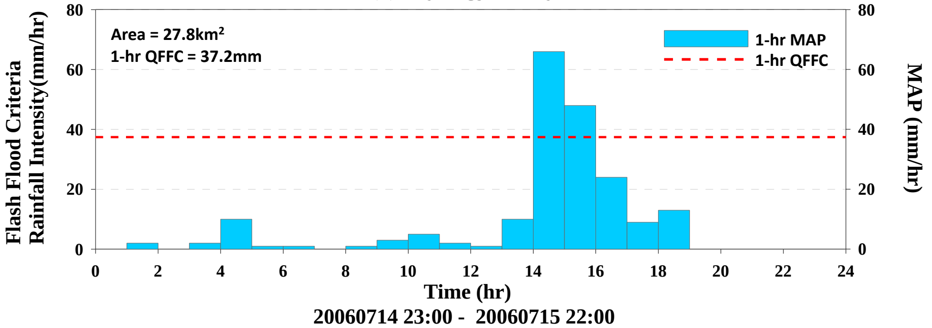
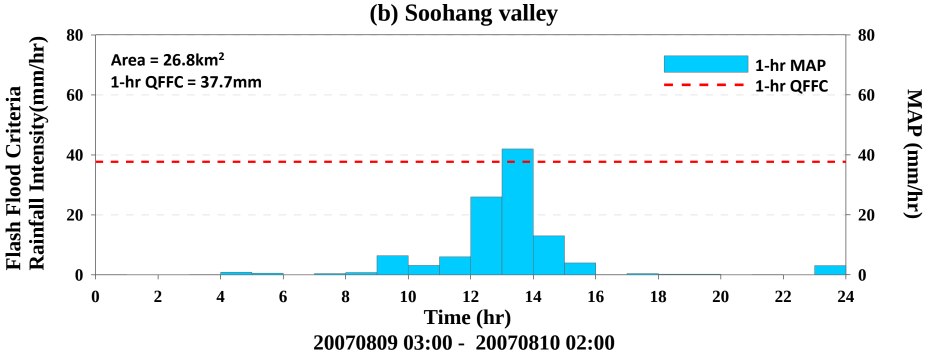


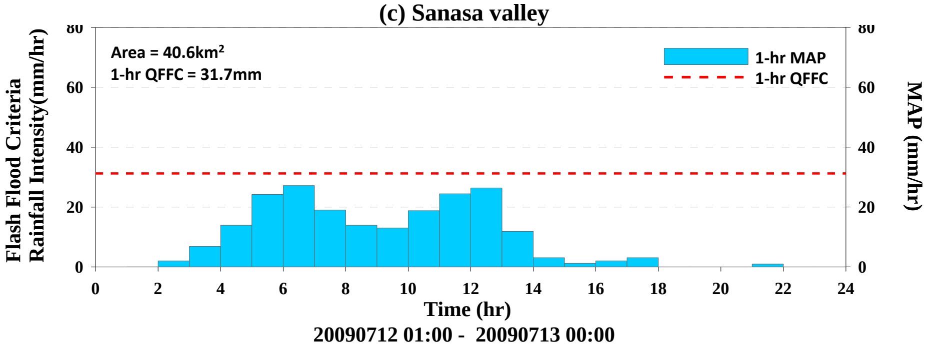
(a) Myungji valley



(b) Soohang valley



(c) Sanasa valley



(d) Danjigol valley

Figure 11: Validation of quantitative flash flood criteria.

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Table 1: ROC score for quantitative precipitation criteria.

		Observed event	
		Positive (OR>FFG)	Negative (OR<FFG)
Virtual event	Positive (VR>FFG)	Hit (H)	False (F)
	Negative (VR<FFG)	Missing (M)	Negative hit (N)

Table 2: Flash flood records collected in the Han River basin.

S. No.	Time	Location	Area (km^2)	Longitude	Latitude	Maximum rainfall (mm/hr)
1	2005.08.03 02:00	Mt. Myungji valley, Gapyeong-gun, Gyeonggi-Do	40.06	37.9447	127.4949	32.1
2	2006.07.15 13:00	Soohang valley, Pyeongchang-gun, Gangwon-Do	27.79	37.5619	128.6087	66.0
3	2007.08.09 16:00	Sanasa valley, Yangpyeong-gun, Gyeonggi-Do	26.83	37.5353	127.5292	42.0
4	2009.07.12 06:00	Danjigol valley, Hoengseong-gun, Gangwon-Do	40.58	37.3974	128.1232	27.2
5	2010.09.11 19:00	Yongchoo valley, Gapyeong-gun, Gyeonggi-Do	44.92	37.8561	127.4832	37.0
6	2011.07.27 05:00	Uidong valley, Gangbuk-Gu, Seoul-Si	36.96	37.6711	127.0060	57.5
7	2011.07.26 17:00	Madangbawii valley, Namyangju-Si, Gyeonggi-Do	46.95	37.7039	127.1008	49.2
8	2011.07.27 08:00	Mt. Namhan valley, Gwangju-Si, Gyeonggi-Do	33.99	37.4786	127.1887	52.1
9	2011.08.03 12:00	Noksoo valley, Gapyeong-gun, Gyeonggi-Do	37.63	37.7764	127.3954	38.1
10	2011.08.09 13:00	Sadam valley, Goesan-gun, Chungbuk	60.98	36.6253	127.8312	22.1
11	2011.08.14 13:00	Gogiri valley, Yongin-Si, Gyeonggi-Do	40.45	37.3599	127.0560	23.2
12	2012.07.15 08:00	Byeongjibangri valley, Gapyeong-gun, Gyeonggi-Do	90.18	37.6080	128.0762	21.5

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Table 3: Regression analysis for parameter estimation using basin area, stream length and slope in the Han River basin.

Parameter	Best-fit regression	Coefficient of determination, R^2	No. of cases
B	$= 15.776A^{0.369}S^{-0.0080}$	0.76	46
H	$= 2.39A^{-0.920}L^{1.174}S^{0.748}$	0.37	46
Sc	$= 2.443A^{-0.278}L^{-0.769}$	0.53	46

Units: B [ft], H [ft], S [ft/mi], Sc [ft/mi], A [mi^2], and L [mi]