Revision according to the reviewer's comments:

We thank you for your constructive review and comments. We have attached answers and the revised manuscript. The comments are numbered by reviewer comment; our responses were written after this symbol (►). We believe that the manuscript is in much better form now.

Reviewer:

In this manuscript you propose a model for predicting (and warning of) flash floods in parts of South Korea. You argue that a soil-water model is an important component for better deriving conditions that lead to flash floods. You also include the concepts of flash flood guidance (FFG), threshold runoff, and simulations of virtual rainfall to arrive at a precipitation-basin area curve that helps predict flash floods. The backbone of your approach seems to be a classifier that allows you to 'predict' flash floods from time series. One could interpret your precipitation-area curve as a decision boundary, although you do not explicitly investigate this concept.

Your topic is clearly of interest to NHESS and a broad international readership, but the way you present your research needs very thorough attention. I suggest restructuring your manuscript, better outlining your methods and assumptions, adding a dedicated discussion section, and carefully revisiting your concept of validation. You could also help readers appreciating the novelty and advances of your contributions by more clearly and critically assessing what you have achieved here.

►*We also agree with your opinion that the submitted manuscript did not fully describe the novelty and advances of study. And there are several ambiguous expressions in the manuscript. Therefore we tried to show the obvious motivation, purpose, and final output of this study in abstract, introduction sections. We added the discussion section for suggesting the meaning, limitation, utilization, and future work of this study. And we rephrased the methodology and results sections for removing ambiguous expression and providing more information with readers.*

※ General Remarks

1. Your abstract could do with more detail on how you validated your predictions, and whether they are reliable enough to allow useful flash-flood predictions (or forecasts). What is the eventual output of your prediction and where can this be used in practice?

►*We added detailed description of methods and key results of validation, indicating the usefulness of the P-A curve in practice (page 1, line 19-22).*

"The proposed P-A curve was validated based on observed flash flood events in different sub-basins. Flash flood occurrences were captured for 9 out of 12 events. This result can be used instead of FFG to identify brief flash flood (less

than 1-hour), and it can provide warning information to decision makers or citizens that is relatively simple, clear, and immediate."

2. The introduction provides some clues why forecasting flash floods is important, but misses opportunities to briefly explain those concepts (especially 'FFG') relevant to your research. Consider making a better case by illuminating more recent case studies of flash floods in South Korea. What is mostly needed for their prediction and why? In this regard, you close the introduction with a somewhat contradictory comment on the need for measuring (antecedent?) soil moisture. Please reconcile that statement and offer a clear overview of your objectives. Which research question is it that you wish to address? Which tools do you use and why?

►*We added the some explanation of the relationship between FFG and the P-A curve in the methods section (page 3, line 1~5).*

"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 a P-A curve for flash flood warning based on FFG due to the lack of observed flash flood events. Thus, a P-A curve was derived by using FFG, but we validated the criteria by using observed flash flood events"

►*We added a literature review related to flash flood studies in South Korea, and we revised the introduction to suggest the research questions and purposes of this study (page 2, line 20 ~32).*

"Bae and Kim (2007) provided the flash flood guidance using the Manning equation, GIUH (geomorphologic instantaneous unit hydrograph), and TOPMODEL (Beven et al., 1994). Lee et al. (2016) generated a gridded flash flood index using the gridded hydrologic components of the TOPLATS land surface model and a statistical flash flood index model. Recent studies have focused on the accuracy and spatial distribution of FFG.

However, 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, the heavy rainfall events have resulted in several flash floods since 2000, such as events in 2005, 2006, 2008 and 2012 at several locations in South Korea. In particular, the hourly maximum rainfall exceeded 50 mm/hr in 2006 and 2011, most of the flash flood events in South Korea were caused by short rainfall duration of less than one hour. It is difficult to capture these flash flood cases using the methods presented in previous studies. Therefore, prompt flash flood warnings are necessary for citizens and decision-makers."

►*We added some reasons to use FFG (page 3, line 3-5).*

“In this study, we proposed quantitative criteria using a P-A curve for flash flood warning based on FFG due to the lack of observed flash flood events. Thus, a P-A curve was derived by using FFG, but we validated the criteria by using observed flash flood events.”

►*And we describe our reasons for using discharge that causes a 0.5m water level increase and SURR in section 3 (page 5, line 7~9; page 6, line 1~5).*

“In this study, the threshold runoff criterion for small streams is a 0.5 m water level increase, as measured from the channel bottom, which is the level that mountain climbers and campers successfully escape from during natural flood damage. The discharge ($Q_{0.5wi}$) that causes a 0.5 m water level increase is defined.”

“Bae and Lee (2011) showed that the SURR simulations are well fitted to observations, and Nash and Sutcliffe model efficiencies in the calibration and verification periods which are in the ranges of 0.81 to 0.95 and 0.70 to 0.94, respectively. Additionally, the behavior of soil moisture depending on the rainfall and the annual loadings of simulated hydrologic components are rational. From these results, an SURR model can be used for simulation of soil moisture.”

3. The methods section I found difficult to follow. You start of with QPC computation and briefly mention the concept of ’virtual rainfall’. Please elaborate more on that so that readers can reproduce the full stream of your methods. Provide (more) mathematical formulations where appropriate, and please do explain all parameters used (some are not referred to). Why use bankfull discharge? Is that the definition for the minimum discharge to cause flash flooding? Assuming steady, uniform flow may also be problematic for flash floods, and you might want to pick that up in the discussion. Equation 3 shows a soil-water content balance that you adapt from the SURR model; how well can you constrain each of the five terms? For example, will evapotranspiration as a function of time be relevant for forecasting flash floods? Clearly you want to specify the timescales that you base your forecasts on. I was unsure about the output of your model. Your use of a receiver-operating-characteristic curve indicates that you classify something, but what exactly, remains vague. Please explain in more detail how you labeled the classes of observed events and how you predicted new classes using SURR.

►*We revised Figure 1 to provide a more detailed description and added some explanation (page 4, line 8~15). This revision makes it clearer how we apply the ROC analysis and how we derive the P-A curve.*

“This study presents a method for deriving a P-A curve that represents the rainfall thresholds occurring during flash floods. The method is based on FFG analysis to avoid the need to estimate soil moisture conditions. Figure 4 presents the overall procedure used to evaluate the quantitative precipitation criteria (QPC) for flash flood warning. First, the mean areal precipitation and FFG were calculated by using topographic, meteorological data for the sub-basins in the study area. To obtain FFG at current time (t), which is a summation of threshold runoff (TR) and soil moisture deficit, threshold runoff at each sub-basin is estimated. The soil moisture conditions from actual rainfalls are simulated by using SURR model, and we

can decide whether a flash flood occurred at certain basin by comparing this FFG value and that from 1-hr prior to the actual rainfall. In this experiment, it is assumed that if the observed MAP is larger than the FFG, a flash flood occurs."

►*We added explanations of all parameters in the equation.*

►*We used discharge at the level of a 0.5 m water level increase from the channel bottom which is the level from which mountain climbers and campers can successfully escape during natural flood damage.*

►*We chose the SURR model because this model can simulate continuously. The long-term hourly runoff and soil-moisture can be simulated through the SURR model. Although evapotranspiration is not directly linked with flash flood forecasting, more realistic soil moisture estimation is possible by considering the evapotranspiration term. We added some references on the applicability of the SURR model (page 6, line 1~5).*

"Bae and Lee (2011) showed that the SURR simulations are well fitted to observations, and Nash and Sutcliffe model efficiencies in the calibration and verification periods which are in the ranges of 0.81 to 0.95 and 0.70 to 0.94, respectively. Additionally, the behavior of soil moisture depending on the rainfall and the annual loadings of simulated hydrologic components are rational. From these results, an SURR model can be used for simulation of soil moisture."

4. I suggest changing the order of the methods and study area section. Providing first a general background on the region of interest and the data available before dealing with the method makes more logical sense to me.

► *We agree, and we have changed the order of the methods and study area section. The revised section order is as follows.*

2. Study Area and Datasets
3. Methods
3.1 QPC Computation
3.2 Flash Flood Guidance (FFG)
3.3 Receiver Operating Characteristics (ROC)

5. The results section starts off with more methods, uncomfortably emphasizing even more the logical disruption between the early sections of your manuscript. You offer some hydraulic geometry that you derive from a multiple regression model, in which the predictors are clearly correlated. This will need some more robust statistical treatment. Further down the section you mention that the predicted and observed timing of flash floods seem to be roughly similar. This is the first explicit mention of comparing predictions with observed data, and thus the motivation for using ROC curves, I presume. If so, please make sure that this core message comes across much earlier. Again, the time steps or measurement/simulation intervals here are critical. Please elaborate. I am a bit suspicious about Fig. 10. Does basin area somehow play a role in estimating rainfall intensity in any of your models? Finally, your validation (section 4.4) needs to be more convincing. You mention that you tested your method on four observed flash floods between 2005 and 2009. How many cases did you use for training your classifier? Can you show some ROC curves (or other performance metrics) for the testing cases?

►*Section 4.1 show the regional regression results for channel geometry. We added more analysis results and references because the main part of our paper is not this section (page 7, line 21~24).*

"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 (Cho et al., 2011). The determination coefficient of hydraulic depth (H) is lower than the other variables. If additional data regarding river cross section are available, the regression equation will be improved."

►*We claimed that FFG shows good performance in South Korea and that a ROC analysis can be applied by using these data instead of actual flash flood events (page 8, line 15-17).*

"As shown in Table 2 and Figure 7, the timing of the flash flood occurrence computed from the FFG model exhibited satisfactory agreement with those from the observed flash flood record."

►*We performed a ROC analysis for all sub-basins. We estimated the virtual rainfall value associated with the peak ROC score. The results showed that virtual rainfall could be estimated as a function of the corresponding sub-basin area. These results show that the threshold for flash flooding can be classified by sub-basin area.*

►*We added the method and assumption of validation (page 9, line 9-13). However, the P-A curve was trained by using FFG rather than actual flash flood events. The ROC score of a specific basin is determined as shown in Figure 8.*

"For the validation of the performance of the P-A curve, the quantitative flash flood criteria for actual flash flood events were applied. This experiment assumed the gauged mean areal precipitation as a prediction. The experiments were assessed whether the prediction exceeded the quantitative flash flood criterion when an actual flash flood event occurred in the basins. If the prediction exceeded the quantitative flash flood criterion, a flash flood warning would be issued. According to the results, the flash flood occurrence was captured for 9 out of 12 events when the criteria were evaluated (Table 4)."

6. Your study could use a formal discussion section, in which you objectively discuss your methods in the light of their assumptions, limitations, and benefits (or advances) compared to previous work. Consider reflecting on how accurately SURR produces the necessary input data; how your classification would change for different time intervals; how your classification deals in general with rare events (for which ROC curves might not be the best of performance metrics); and what you consider as possible future improvements to your model.

►*We added a discussion session, and this section was organized into two sub-sections (5.1Uncertainty of flash flood forecasting methods, 5.2 Utilization of a P-A curve for flash flood forecasting). The contents of 5.1 are different in this study from those in previous studies. The assumptions, limitations, and future work of this study are described (page 9 line 26~page10 line 17). The contents of 5.2 are reviews of flash flood forecasting systems used abroad, and the section discusses the usefulness of the P-A curve (page 10 line 18~page 11 line 3).*

“5 Discussion

5.1 Uncertainty of flash flood forecasting method

There are many flash flood forecasting methods. The methods can be divided into three categories: flow comparison methods, rainfall comparison methods, and flash flood susceptibility assessment. The proposed P-A curve is rainfall threshold that included with the rainfall comparison methods like FFG. The rainfall comparison method is a popular tool for warning about flash floods, and this method is commonly used for flash flood forecasting. However, the previous rainfall threshold method has some limitations, recent studies tried to improve warning accuracy by using distributed physical hydrological modeling (Kobold and Brilly, 2006; Reed et al., 2007; Norbiato et al., 2009). Hapuarachchi and Wang (2008) suggested that physically based distributed hydrological models are more appropriate than data-driven models and conceptual hydrological models for flash flood forecasting. However, the most important thing of flash flood forecasting is a providing the warning information to decision makers or citizens with relatively simple, clear, and immediate. It means that not only the sophistication but also promptness with reasonable accuracy also is necessary for flash flood forecasting. In this respect, this study proposed quantitative criteria using P-A curve for flash flood warning based on FFG. The key advantage of this method is that it doesn’t need any further calculation compared to the other rainfall comparison method. In other word, the proposed criteria and methodology will serve as an important tool for issuing flash flood warnings based on only rainfall information.

However, this study has some assumptions and limitations. The P-A curve is based on the FFG, not real observed flash flood events because there is lack of observed flash flood events. In addition, the proposed P-A curve has some uncertainties from lots of sources such as soil moisture estimation (SURR), Threshold runoff estimation method, finding the optimal P-A curve by using ROC method, collection of actual flash flood events etc. But, these problems are not confined to this study because the phenomena triggering flash flood are very complex. Any flash flood forecast method has also large uncertainties due to input data errors, and modelling errors. Thus, it is necessary for understanding of the uncertainty from all these sources for decision making in flood warning because good uncertainty estimates of flash flood forecasts can add credibility to the forecast system.

5.2 Utilization of a P-A curve for flash flood forecasting

Some flood forecasting systems have been developed and operated in some countries (Mogil et al., 1978; Sweeney, 1982; Mason, 1982; Alfieri et al., 2012). Northern America has a flash flood forecasting system using gridded flash flood guidance (GFFG). This system uses multi-sensor precipitation estimates and forecasts based on NEXRAD (Next Generation Weather Radar), rain gauges and NWP (numerical weather prediction) model outputs. The European Flood Forecasting System (EFFS) used the LISFLOOD-FF for generating river flow and LISFLOOD-FP to model the overbank flows and inundation areas, and they use gauged rainfall, radar rainfall, and NWP model outputs (Roo et al., 2003). ALERT in Australia uses a hydrological model with real-time rainfall and water level data. They also assess the severity of flooding using simple *manual guides (look-up tables). Thus, the ideal flash flood system needs to combine two approaches. It must present the criteria used to judge flash floods in an intuitive way for very short-term flash floods (less than 1 hour). It must also make predictions with sophisticated modeling using a physical distributed model for flash floods with greater than a 3-hour duration. Therefore, the FFGC (flash flood guidance criteria) are used for short-term flash floods.*

This study focused on using a P-A curve, and it assessed the outcome when using only gauged rainfall data. However, the quality of flash flood forecasting depends on the quality of the rainfall data. Additionally, reliable rainfall forecasts with adequate lead-time and accuracy are essential for flash flood forecasting. In general, the gauged rainfall, radar data (Sinclair and Pegram, 2005; Mazzetti and Todini, 2009), and satellite data (Soorooshian et al., 2000; Kubota et al., 2007) have been used for quantitative precipitation estimates (QPEs), and some studies have used multiple precipitation sources (Sokol, 2006; Chiang et al., 2007). Therefore, this method is necessary for assessing the applicability of using rainfall data obtained from various sources."

7. Your conclusions mostly summarize your data. You report a high prediction potential, which is partly based on finding the optimal ROC scores in the first place, right? You state that 'The flash flood warning threshold can be best represented as a function of sub-basin area' (page 8/line 27). What does that mean and what is its practical relevance for warning? You may want to report statistical uncertainties for your generalized precipitation-area in this context.

►*We added some sentences as described below*

"These results mean that the threshold for 1-hr flash flood prediction can be classified according to sub-basin area.".

►*We described the statistical uncertainties in the discussion section (page 10 line 10~17).*

8. The reference list appears a bit short. I imagine that other groups must be working on prediction of flash floods elsewhere.

►*We performed that the literature review related to flash flood forecasting and added twenty papers as references (page 11, line 22~page 13, line 32).*

9. Figures: #1 is OK, if you add some explanatory detail to the caption; please explain all abbreviations. #2 needs geographic coordinates and larger fonts. #3a and # 4a need units for 'sub-basin area'; are #3b and #4b really necessary? Histogram bins in #5b may be too wide: what is it that you wish to state here? #6 needs explanations of color codes. #7 needs larger fonts and explanation of abbreviations. #8: it is unclear what the minimum and maximum numbers refer to. #9: please explain orange shades. #10: please explain red and blue circles. Overall, you may want to use your captions for informing readers more about the contents and messages of your figures.

►*We revised Figure 1 to provide more detail.*

► *We added the unit of sub-basin area in Figure 3 and Figure 4.*

► *Figure 3b and 4b are necessary for the understanding of sub-basin area distribution.*

► *The interval of the histogram bins of Figure 5b was changed from 5 to 3.*

► *We added some explanation of the color codes in Figure 6*

► *We changed the font size and explained the abbreviations of Figure 7*

► *The minimum value of Figure 8 was revised*

► *We explained the orange shades of Figure 9 and the red and blue circles in Figure 10*

10. Is Table 1 necessary?

► *We think that this table is necessary because table 1 shows readers the concept of ROC analysis.*

11. Please ask a native speaker to check your manuscript. I have noticed numerous formal and potentially ambiguous errors in the text, but these errors are too many to list in detail below. Therefore, I only give only a few examples in the line-specific suggestions below.

► *We ordered English editing from AJE (American Journal Experts) and the manuscript has been revised by native English-speakers persons. We believe that these edits have solved the English grammar problems and improved the readability of the text.*

※ Specific Suggestions

1. (1/8) Delete 'with short duration'. The term 'flash flood' implicates that.

► *We deleted this term.*

2. (1/9) 'required to cause minor flooding' - Why minor flooding? Please provide a brief definition of what you mean by 'minor' here.

► *We revised that sentence as shown below (page 1, line 11~13). Generally, the threshold runoff of FFG is based on a 1~2 year return period flood.*
"The quantitative criteria is calculated based on Flash Flood Guidance (FFG) which was defined as the depth of rainfall of a given duration required to cause frequent flooding (1~2 year return period) at the outlet of a small stream basin"

3. (1/12) Please spell out 'ROC'. .

► *We added the complete spelling of ROC.*

4. (1/15) 'highly' should read 'more'?

► *We revised 'highly' to 'more'*

5. (1/16) ’obtained for rainfall rates of 42, 32 and 20 mm/h’ - It is unclear why or how you picked those rates. Please explain.

►*We revised the sentence as shown below, and we added a more detailed description (page 1, line 16~17).*
“For the brief description of the P-A curve, the generalized thresholds for flash flood warning can be suggested for rainfall rates of 42, 32 and 20 mm/h in sub-basins with areas of 22~40 km², 40~100 km² and >100 km², respectively.

6. (1/17) ’actual’ means ’observed’ or ’measured’? Please summarize briefly the results from your validation.

►*We revised ‘actual flash flood events’ to ‘observed flash flood events’ (page 1, line 18).*
►*We added the validation results shown below (page 1, line 17~19).*
“The proposed P-A curve was validated based on observed flash flood events in different sub-basins. Flash flood occurrences were captured for 9 out of 12 events.”

7. (1/20) ’the short-duration flash flood frequently occurred’ should read ’the flash floods occur frequently’.

►*We revised ‘the short-duration flash flood frequently occurred’ to ‘flash floods occur frequently’*

8. (1/24) ’managing flash flood control’ - What do you mean by that specifically?

►*We revised that sentence as below (page 1, line 27~28).*
“It is difficult to monitor and forecast flash floods due to the unusually short response time for these natural disasters.”

9. (1/25) ’the climate change has increased’ could read ’climate change may have likely increased’.

►*We revised ‘the climate change has increased’ to ‘climate change likely increased’ (page 1, line 28)*

10. (1/27) What sort of ’technology’ do you mean? Or did you mean ’methodology’ instead?.

►*We revised that sentence as shown below (page 1, line 29~30).*
“Therefore, reliable flash flood forecasting methods are necessary for flash flood response”

11. (1/28) ’For deciding flash flood occurrence,’ - Unclear.

►*We revised ‘For deciding flash flood occurrence’ to ‘To judge flash flood occurrence’ (page 2, line 1).*

12. (2/1) ’flash flood vulnerability’ - This refers to potential damage. Is that what you meant?

►*We revised ‘flash flood vulnerability’ to ‘flash flood vulnerability (possibility of flash flood occurrence and degree of danger)’ (page 2, line 3~4).*

13. (2/5) ’simulation to establish the observed frequency distribution’ - Contradictory. Why simulate something to establish observations? Perhaps change the wording here?

►*This phrasing is correct, because generally there are not enough runoff data in a small basin, so we need to simulate runoff data using a hydrological model. However, we revised this sentence as shown below to improve the sentence (page 2, line 6~7).*
“However, this approach has some limitations for real-time flash flood forecasting because it requires long historical data and hydrological simulation to establish a flash flood modeling system.”

14. (2/6) ’comparing forecast flow with flooding flow’ - How about ’comparing forecast with observed flows’?

►*We revised ‘comparing forecast flow with flooding flow’ to ‘comparing forecasts with observed flows’*

15. (2/7) Delete ’eminent’.

►*We deleted ‘eminent’.*

16. (2/9) ’understood by the general public’ - It may be useful to briefly explain the concept here.

►*We revised the sentence as shown below (page 2, line 10~12).*
“This method is commonly used for flash flood forecasting, as it is easily understood by the general public because it provides a qualitative criterion that can be used to intuitively determine whether a flash flood will occur.”

17. (2/13-15) So what did those studies find out?

►*We added their findings as below (page 2, line 19~20).*
“They claimed that physically based methodologies are more appropriate for flash flood forecasting”

18. (2/13-15) ’the hourly maximum rainfall exceeded 50mm/hr and 60 mm/hr in 2006 and 2011’ - Difficult to assess the relevance of these rates without any background information on rainfall characteristics in the region.

►*We added the climatic characteristic of the basin in Section 2 Study area and Datasets (page 3, line 25-28)*
“The average annual precipitation was 1,390 mm, and the annual mean temperature was 11.5 ℃ over the 30 years of weather data from 1980 to 2009. More than 70% of the annual precipitation occurs during the flood season (June, July, August and September). The probability rainfalls for 1-hr at Seoul station are 52 mm/hr, 74 mm/hr, and 91 mm/hr for 3-year, 10-year, and 30-year return periods, respectively.”

19. (2/23) Delete ’exquisitely’. Please also check grammar in this sentence. I think I know what you mean here, but you would be really well advised to seek the help of a native speaker for rephrasing many similar statements in your manuscript.

►*We removed ‘exquisitely’ and revised the sentence as shown below (page 2, line 33~34).*
“It is less important to estimate the soil moisture or runoff in the regions where flash floods occur frequently with short duration because the response time for a flash flood is limited”

20. (3/9) What are ’ROC scores’?

►*We added some description of the ROC score (page 6, line 25~28).*
“However, a ROC curve cannot be clearly indicated for objects that are more accurate than other objects. Wilk (2006) suggested an ROC Score which is the area of ROC curves. An ROC score can be calculated by using HR and FAR, as shown in Eq. (6)”

21. (3/15) ’method used to compute FFG is the opposite’ - So what is the main output of FFG?

►*We revised those sentences as shown below (page 4, line 24~26).*
“The method used to compute FFG involves procedures opposite to those of a rainfall-runoff model. In other words, FFG is defined as the depth of rainfall over a given duration needed to initiate flooding at the outlet of a small stream basin. It is generally estimated for 1-, 3-, and 6-hour durations.”

22. (3/19) ’over a given duration tr required to’ - Please use italics for all parameters that you introduce.

►*We changed all parameters to italics (page 4, line 29~page 7, line 24).*

23. (3/24) What is the unit of the 'unit hydrograph peak', if you use differing metric systems? Please attend to Equation 1: in my copy of the PDF it looks as if A is an exponent in the denominator.

► *The units of* q_{pR} are *cfs/mi*^{2}*/in. We added the units in the manuscript (page 5, line 4).*
►*We revised Equation 1 (page 5, line 3).*

24. (4/4) 'which represents current soil conditions' - What do you mean by 'current'? During or before the flash flood?

►*We revised that sentence as shown below (page 5, line 17).*
"To derive the rainfall-runoff curve which represents soil conditions during flash flood event"

25. (4/9) 'this model uses estimates soil moisture' - Ambiguous. Does the model use estimates of soil moisture or does it estimate soil moisture itself? That is a big difference.

►*The SURR model can estimate the soil moisture based on simulations of runoff and actual evapotranspiration. Thus, SURR can generate soil moisture, surface runoff, ground runoff, and actual evapotranspiration. SURR is described in detail in the manuscript (page 5, line 17~page 6, line 5).*

26. (4/27) Please explain parameters in Equations 4 and 5.

►*We added an explanation of the parameters in Equation 4 and 5 (page 6, line 11~13).*
"H and M represent hits and misses for predictions of when a flash flood will occur (OR > FFG). F and N represent false and negative hits for when a flash flood does not occur (OR < FFG)."

27. (5/5) 'line segments that coincide with the left boundary and upper boundary of the ROC diagram' - You could simply say that, for a perfect prediction, the ROC curve has to pass through (0, 1) or the upper left point of the graph.

►*The upper left point of the graph represents perfect prediction. We added this sentence to the manuscript (page 6, line 20~21).*

28. (5/7) 'ROC curves associated with real forecasts generally fall between these two extremes and plot above and to the left of the 45-degree diagonal' - Not sure what you mean by a 'real' forecast.

►*We deleted this sentence because it is not necessary. However, we added some details about the ROC score.*

29. (5/15) 'were delineated' - How did you delineate those basins? Their size spans three orders of magnitude, so what was the underlying rationale?

►*We delineated the sub-basin using 30 × 30 m DEM. The parameter of flow accumulation should be set to delineate the area of sub-basins in the range of 0~100 km*^{2}.

30. (5/19) 'omitted from further analysis' - So you did not consider all basins with reservoirs further?

►*Correct, we did not consider reservoir effects.*

31. (5/21) ʼfiltering' - This means you had some preconception about basin area influencing flash-flood potential? It might be good to give more detail here.

►*We revised those sentences as follows (page 3, line 16~17).*
"Among the 660 sub-basins, we selected head water basins and mountainous basins and removed the artificial river basins. A total of 200 sub-basins were selected, as shown in Figure 3a."

32. (5/28) ʼsoil moisture conditions were estimated' - Please be more specific about the spatial resolution, time intervals, and accuracies of those estimates.

►*The SURR model was run for the hourly time series with a sub-basin scale. We now discuss the accuracy of the SURR model (page 6, line 1~5).*
"Bae and Lee (2011) showed that the SURR simulations are well fitted to observations, and Nash and Sutcliffe model efficiencies in the calibration and verification periods which are in the ranges of 0.81 to 0.95 and 0.70 to 0.94, respectively. Additionally, the behavior of soil moisture depending on the rainfall and the annual loadings of simulated hydrologic components are rational. From these results, an SURR model can be used for simulation of soil moisture."

33. (5/30) ʼflood information was obtained through different sources, including print and electronic media' - How homogeneous and reliable is that information?

►*Yes. The information about flash flood events is not homogeneous which is the source of flash flood forecasting uncertainty. We described this uncertainty in the discussion session.*

34. (6/1) ʼmultiple flash flood events' - Perhaps this is something you may wish to elaborate on a bit more?

►*We revised that sentence as follows (page 4, line 1~2).*
"In 2011, several flash flood events occurred with different areas and dates."

35. (6/15) ʼwere investigated and included in the regression equation' - Please describe this in more detail. You note that some of the predictors in your regression model are correlated, but you do not seem to do anything about this.

►*We added more analysis of the results (page 7, line 21~24).*
"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 (Cho et al., 2011). The determination coefficient of hydraulic depth (H) is lower than the other variables. If additional data regarding river cross section are available, the regression equation will be improved."

36. (6/25) ʼThreshold runoff values were computed' - How?

►*We revised that sentence as follows (page 7, line 26~27).*
"The threshold runoff values were computed for effective rainfall durations of 1-hour in the 200 selected sub-basins by using the Manning equation and GIUH method, as mentioned in section 2.2."

37. (6/27) Can you measure runoff rate to one tenth of a mm/h?

►*The threshold is calculated by using the Manning equation and GIUH; it is not measured. The unit of threshold runoff is mm/hr or cm/hr.*

38. (6/30) ʼflooding season, i.e., July, August and September' - You could explain more about this flooding season in the study area descriptions; international readers might welcome this information.

►*We added the climatic characteristic of the basin in Section 2 Study area and Datasets (page 3, line 25~28).*
"The average annual precipitation was 1,390 mm, and the annual mean temperature was 11.5 ℃ over the 30 years of weather data from 1980 to 2009. More than 70% of the annual precipitation occurs during the flood season (June, July, August and September). The probability rainfalls for 1-hr at Seoul station are 52 mm/hr, 74 mm/hr, and 91 mm/hr for 3-year, 10-year, and 30-year return periods, respectively."

39. (7/16) 'times of flash flood occurrence computed from the FFG model exhibited satisfactory agreement' - Is it the timing that you wish to classify correctly?

►*We changed 'times' to 'timing'*

40. (7/21) 'As expected, the minimum ROC score was 0.50' - You can sometimes get lower values than that.

►*The range of ROC scores is 0.5 to 1.0 as shown in Figure 8 and Figure 9. We added more description of the ROC score (page 6, line 21-25).*
"However, a ROC curve cannot be clearly indicated for objects that are more accurate than other objects. Wilk (2006) suggested an ROC Score which is the area of ROC curves. An ROC score can be calculated by using HR and FAR, as shown in Eq. (6)."

41. (8/12) 'estimated values of 1-hr QFFC' - Do you have measured values for a validation?

►*We have the timing and locations of the flash flood. We can analyze the flash flood criteria when flash floods occur.*

42. (8/29) 'optimum threshold for flash flood warning in a sub-basin' - Slight repetition.

►*We replaced 'optimum threshold for flash flood warning in a sub-basin' with 'it'.*

43. (9/4) 'which is divided with short and long-duration' - And how do set the threshold between 'short' and 'long'?

►*We revised that sentence as follows (page 11, line 16~17).*
"Therefore, the development of a coupled flash flood forecasting system, which is divided into short (less than 1 hr) and long-duration (greater than 3 hrs) is necessary for managing flash flood efficiently."

Revision according to the reviewer's comments:

We thank you for your constructive review and comments. We have attached answers and the revised manuscript. Our responses were written after this symbol (►). We believe that the manuscript is in much better form now.

Reviewer #2:

Important topic of high relevance. The paper is generally of a good structure and gives good insight in what has been done in the project. But not really a new approach, already been done in similar ways in other regions. Following open issues should be addressed in the publication: The cells of convective events are much smaller than the catchments described in the paper, so in the real world only part of the catchment will be in the focus of the precipitation event. There is little info about what type of precipitation measurement has been used, are this ground measurements or radar or some combination of it? What is the resolution of the measurement? As the convective events are difficult to measure, the uncertainty applied by this also should be discussed. In the publication a lot of abbreviations are being used, this makes it hard to read, especially as they are not commonly used abbreviations, so better replace them by the full text. As the timely distribution of a rainstorm event also has high impact on the runoff, this should be tackled as well. Some more words should be spend on how the results can be used, in what extent are the usable for warning issues and how false warnings can be handled. Who is the planned end user of the thresholds?

►*We revised the paragraph and added a description of the precipitation dataset as shown below (page 3, line 22~25).*
"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). Rain gauges recorded data at 114 locations, and the resolution of each station was approximately 217 km^2 (approximately 15 x 15 km)."

►*We added a discussion section about the sources of uncertainty problems with this method (page 9 line 26~page10 line 17)*
"5.1 Uncertainty of flash flood forecasting method
There are many flash flood forecasting methods. The methods can be divided into three categories: flow comparison methods, rainfall comparison methods, and flash flood susceptibility assessment. The proposed P-A curve is rainfall threshold that included with the rainfall comparison methods like FFG. The rainfall comparison method is a popular tool for warning about flash floods, and this method is commonly used for flash flood forecasting. However, the previous rainfall threshold method has some limitations, recent studies tried to improve warning accuracy by using distributed physical hydrological modeling (Kobold and Brilly, 2006; Reed et al., 2007; Norbiato et al., 2009). Hapuarachchi and Wang (2008) suggested that physically based distributed hydrological models are more appropriate than data-driven models and

conceptual hydrological models for flash flood forecasting. However, the most important thing of flash flood forecasting is a providing the warning information to decision makers or citizens with relatively simple, clear, and immediate. It means that not only the sophistication but also promptness with reasonable accuracy also is necessary for flash flood forecasting. In this respect, this study proposed quantitative criteria using P-A curve for flash flood warning based on FFG. The key advantage of this method is that it doesn't need any further calculation compared to the other rainfall comparison method. In other word, the proposed criteria and methodology will serve as an important tool for issuing flash flood warnings based on only rainfall information.

However, this study has some assumptions and limitations. The P-A curve is based on the FFG, not real observed flash flood events because there is lack of observed flash flood events. In addition, the proposed P-A curve has some uncertainties from lots of sources such as soil moisture estimation (SURR), Threshold runoff estimation method, finding the optimal P-A curve by using ROC method, collection of actual flash flood events etc. But, these problems are not confined to this study because the phenomena triggering flash flood are very complex. Any flash flood forecast method has also large uncertainties due to input data errors, and modelling errors. Thus, it is necessary for understanding of the uncertainty from all these sources for decision making in flood warning because good uncertainty estimates of flash flood forecasts can add credibility to the forecast system."

►*We changed some abbreviations to full names (TR, QFFC) .*

►*We added a discussion section about utilization of a P-A curve (page 10, line 18~ page 11, line 3).*

"5.2 Utilization of a P-A curve for flash flood forecasting

Some flood forecasting systems have been developed and operated in some countries (Mogil et al., 1978; Sweeney, 1982; Mason, 1982; Alfieri et al., 2012). Northern America has a flash flood forecasting system using gridded flash flood guidance (GFFG). This system uses multi-sensor precipitation estimates and forecasts based on NEXRAD (Next Generation Weather Radar), rain gauges and NWP (numerical weather prediction) model outputs. The European Flood Forecasting System (EFFS) used the LISFLOOD-FF for generating river flow and LISFLOOD-FP to model the overbank flows and inundation areas, and they use gauged rainfall, radar rainfall, and NWP model outputs (Roo et al., 2003). ALERT in Australia uses a hydrological model with real-time rainfall and water level data. They also assess the severity of flooding using simple manual guides (look-up tables). Thus, the ideal flash flood system needs to combine two approaches. It must present the criteria used to judge flash floods in an intuitive way for very short-term flash floods (less than 1 hour). It must also make predictions with sophisticated modeling using a physical distributed model for flash floods with greater than a 3-hour duration. Therefore, the FFGC (flash flood guidance criteria) are used for short-term flash floods.

This study focused on using a P-A curve, and it assessed the outcome when using only gauged rainfall data. However, the quality of flash flood forecasting depends on the quality of the rainfall data. Additionally, reliable rainfall forecasts with adequate lead-time and accuracy are essential for flash flood forecasting. In general, the gauged rainfall, radar data

(Sinclair and Pegram, 2005; Mazzetti and Todini, 2009), and satellite data (Soorooshian et al., 2000; Kubota et al., 2007) have been used for quantitative precipitation estimates (QPEs), and some studies have used multiple precipitation sources (Sokol, 2006; Chiang et al., 2007). Therefore, this method is necessary for assessing the applicability of using rainfall data obtained from various sources. "

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~~. The quantitative criteria is calculated based on Flash Flood Guidance (FFG) which was defined as the depth of rainfall of a given duration required to cause frequent~~minor~~ flooding (1~2 years return period) 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 (receiver operating characteristics) 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 because ~~due to the reason that~~ the precipitation threshold with a short duration is ~~highly~~ more related to basin area than any other variables. For a brief description of the P-A curve, ~~G~~generalized thresholds for flash flood warnings ~~were~~ can be suggested ~~obtained~~ for rainfall rates of 42, 32 and 20 mm/h in sub-basins with areas of 22~40 km², 40~100 km² and >100 km², respectively. The proposed P-A curve was validated based on observed ~~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.~~ Flash flood occurrences were captured for 9 out of 12 events. ~~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.~~ This result can be used instead of FFG to identify brief flash flood (less than 1-hour), and it can provide warning information to decision makers or citizens that is relatively simple, clear, and immediate.

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~~It is difficult to~~difficulties in~~ monitor and forecast ~~managing~~ flash floods ~~control~~ due to the unusually short response time for~~among~~ these ~~nature~~ natural disasters. Additionally, climate change likely increased~~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 methods ~~odel i~~are~~s~~ necessary for flash flood response.

To judge ~~For deciding~~ flash flood occurrence, there are three methods: ~~which are the~~ flash flood susceptibility assessment, the flow comparison method, and the rainfall comparison method (Hapuarachchi et al., 2011). ~~The f~~Flash flood susceptibility assessment can be considered ~~as~~ a useful first step in determining the contributing factors to the flash flood vulnerability (possibility of flash flood occurrence and degree of danger) of a catchment using limited data (Collier and Fox, 2003). The flow comparison method ~~is to~~ compares 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 a flash flood modeling system. The rainfall comparison method compares threshold rainfall causing flooding flow ~~to~~with the forecast rainfall instead of comparing forecast ~~flow~~ with observed ~~flooding~~ flows. This method is a~~n~~ ~~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 because it provides a qualitative criterion that can be used to intuitively determine whether a flash flood will occur.

~~However, s~~Some recent studies suggest~~ed~~ the limitations of FFG (Norbiato et al., 2008; Montesarchio et al., 2011~~;~~ ~~Hapuarachchi et al., 2011~~; Gourley et al., 2012). The limitations of FFG are in the assumptions of spatially/temporally uniform rainfall and linear response~~s~~, and the use of regional relationships to make inferences about ungauged locations. FFG performance in ungauged basins is less accurate (Norbiato et al., 2008). ~~The r~~Recent studies tried to improve the warning accuracy. Schmidt et al. (2007) proposed a raster-based method to derive a gridded FFG (GFFG). Gourley et al. (2012) reported that FFG performs better than GFFG, but GFFG can detect spatial variability. Miao et al. (2016) established a strategy for flash flood warning that is based on the definition of rainfall threshold using distributed hydrological model. They claimed that physically based methodologies are more appropriate for flash flood forecasting.

In South Korea, flash flood studies have also been performed. Bae and Kim (2007) provided the flash flood guidance using the Manning equation, GIUH (geomorphologic instantaneous unit hydrograph), and TOPMODEL (Beven et al., 1994). Lee et al. (2016) generated a gridded flash flood index using the gridded hydrologic components of the TOPLATS land surface model and a statistical flash flood index model. Recent studies have focused on the accuracy and spatial distribution of FFG. However, 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, the heavy rainfall events have resulted in several flash floods since 2000, such as events in 2005, 2006, 2008 and 2012 ~~in~~at several locations in South Korea~~Geyonggi-do, Gangwon Inje, Gyeongsanbuk-do, and Gangwon Hoengseong,~~

respectively. In particularEspecially, the hourly maximum rainfall exceeded 50 mm/hr and 60 mm/hr in 2006 and 2011, ., most of the flash flood events in South Korea were caused by short rainfall duration of less than one hour. It is difficult to capture these flash flood cases using the methods presented in previous studies. Therefore, prompt flash flood warnings are necessary for citizens and decision-makers.

It is less important to exquisitely estimate the soil moisture or runoff in the regions where the flash floods occur frequently with short rainfall duration because the response time for a flash flood is limited. flash floods do not wait the warning of flash flood forecasting system. It is necessary to develop the criteria for deciding intuitively judging the likelihood of 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 a P-A curve for flash flood warning based on FFG . due to the lack of observed flash flood events. Thus, a P-A curve was derived by using FFG, but we validated the criteria by using observed flash flood events. Additionallylso, 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 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 km^2, or approximately 23% of the South Korean territory (Figure 1). The 660 sub-basins with areas of 0.1~ 179.8 km^2 were delineated using ArcGIS (as shown in Figure 2a). Figure 2b shows the relative frequencies of sub-basins with areas in different ranges. The average area of a sub-basin was 38.5 km^2, with a standard deviation of 25.7 km^2. Most of the sub-basins were in the range of 20~40 km^2, 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, we selected head water basins and mountainous basins and removed artificial river basins. A total of 200 sub-basins were selected, as shown in Figure 3a. Figure 3b shows the relative frequencies of the areas of the selected sub-basins. The average area of a selected basin was 43.1 km^2, with a standard deviation of 19.8 km^2.

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). Rain gauges recorded data at 114 locations, and the resolution of each station was about approximately 217 km^2 (approximately 15 x 15 km). The average annual precipitation was 1,390 mm, and the annual mean temperature was 11.5 ℃ over the 30 years of weather data from 1980 to 2009. More than 70% of the annual precipitation occurs during the flood season (June, July, August and September). The probability rainfalls for 1-hr at Seoul station are 52 mm/hr, 74 mm/hr, and 91 mm/hr for 3-year, 10-year, and 30-year return periods, respectively. 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 from various sources, including print and electronic media, covering an 8-year period (2005–2012). Table 1 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. In 2011, several flash flood events occurred with different areas and dates.

~~2~~ 3 Methods

3~~2~~.1 QPC Computation

This study presents a method for deriving a P-A curve that represents the rainfall thresholds occurring during flash floods. The method is based on FFG analysis to avoid the need to estimate soil moisture conditions. Figure ~~1~~ 4 presents the overall procedure used to evaluate the quantitative precipitation criteria (QPC) for flash flood warning. First, the mean areal precipitation and FFG were calculated by using topographic, meteorological data for the sub-basins in the study area. To obtain FFG at current time (t), which is a summation of threshold runoff (TR) and soil moisture deficit, threshold runoff~~TR~~ at each sub-basin is estimated. ~~And, t~~The soil moisture conditions from actual rainfalls are simulated by using SURR model~~.~~, ~~A~~and we c~~then we c~~an decide whether a flash flood occurred at certain basin ~~is occurred or not~~ by comparing this FFG value and that from 1-hr prior to the ~~time ahead~~ actual rainfall. In this experiment, it is assumed that if the observed MAP is larger than the FFG, a flash flood occurs.

~~To obtain the QPC for flash flood warning,~~ ROC analysis is used to obtain the QPC for the flash flood warning, and 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 the 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 virtual 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. For a detailed description of Threshold runoff, FFG, SURR, and the estimation of the ROC score refer to sections 3.2 and 3.3.

~~2~~3.2 Flash Flood Guidance (FFG)

The method used to compute FFG -involves procedures opposite to those of a rainfall-runoff model. In other words, FFG is defined as the depth of rainfall over~~f~~ a given duration needed to initiate ~~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 an amount of excess ~~the amount of runoff, or~~ rainfall ~~excess,~~ over a given duration tr~~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~~.~~ ~~T~~wh~~h~~ich~~s~~ is expressed mathematically as follows:

$$Q_p = q_{pR} \times R \times A \quad \text{or} \quad R = \frac{Q_p}{A \times q_{pR}} \tag{1}$$

where Q_p is the flood flow (cms or cfs), q_{pR} is the unit hydrograph peak (cfs/mi^2/in) 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 threshold runoff criterion for small streams is a 0.5 m water level increase, as measured from the channel bottom, which is the level that mountain climbers and campers successfully escape from during natural flood damage. ~~the~~ The ~~bankfull~~ discharge ($Q_{0.5wi}$) that causes a 0.5 m water level increase is defined. It ~~)~~ was computed from channel geometry and roughness characteristics using Manning's formula for steady, uniform flow (Chow et al., 1988):

$$Q_{0.5wi} = B_{0.5wi} D_{0.5wi}^{5/3} S_c^{0.5} / n \tag{2}$$

where $B_{0.5wi}$ is the channel width at ~~bankfull~~ 0.5 m water level (m), $D_{0.5wi}$ is the hydraulic depth at 0.5 m water level ~~bankfull~~ (m), S_c is the local channel slope (dimensionless), and 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 represent~~s~~s ~~current~~ soil conditions during a flash flood event, 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:

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

where $SW(t)$ is the soil water content (mm), $P(t)$ 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. Additional detailed mathematical descriptions of the components~~More detailed mathematical descriptions of the components~~ were provided by Bae and Lee (2011). Bae and Lee (2011) showed that the SURR simulations are well fitted to observations, and Nash and Sutcliffe model efficiencies in the calibration and verification periods which are in the ranges of 0.81 to 0.95 and 0.70 to 0.94, respectively. Additionally, the behavior of soil moisture depending on the rainfall and the annual loadings of simulated hydrologic components are rational. From these results, an SURR model can be used for simulation of soil moisture.

3~~2~~.3 Receiver Operating Characteristics (ROC)

The Receiver Operating Characteristics (ROC) approach, or the ROC curve method, was originally proposed to ~~analyze~~ analyse 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. *H* and *M* represent hits and misses for predictions of when a flash flood will occur (OR > FFG). *F* and *N* represent false and negative hits for when a flash flood does not occur (OR < FFG).

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

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

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. The upper left point of the graph represents perfect prediction. –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. However, a ROC curve cannot be clearly indicated for objects that are more accurate than other objects. Wilk (2006) suggested an ROC Score which is the area of ROC curves. An ROC score can be calculated by using *HR* and *FAR*, as shown in Eq. (6) .

$$ROC\ Score = \left\{ \sum_{i=1}^{n} \begin{matrix} \frac{1}{2}(HR_i + 0.0)(FAR_i - 0.0) + \frac{1}{2}(HR_{i+1} + HR_i)(FAR_{i+1} - FAR_i) \\ + \cdots, + \frac{1}{2}(1 + HR_{i+n})(1 - FAR_{i+n}) \end{matrix} \right\} \quad (6)$$

~~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 discharge ($Q_{0.5wi}$) that causes 0.5 water level~~The bankfull flow Q_{bf}~~ increase is used as a flood flow in this study. The calculations of $Q_{0.5wi}$~~$_{bf}$~~ 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 channel ~~bankfull~~ width (B~~B~~), hydraulic depth (H~~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~~A~~) were investigated using a power regression equation as follows:

$$X = \alpha A^{\beta} \quad (~~6~~7)$$

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:

$$X = \alpha A^{\beta} L^{\gamma} S^{\delta} \quad (~~7~~8)$$

where α, β, γ and δ are regression coefficients. A correlation analysis was performed to ~~analyze~~ analyse the relationship between the parameters (B, H, and S_c) and basin characteristics (A, L and S). As shown in Table 3, the ~~bankfull~~ channel 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 (Cho et al., 2011). The determination coefficient of hydraulic depth (H) is lower than the other variables. If additional data regarding river cross section are available, the regression equation will be improved.

4.2 Threshold runoff and FFG

The ~~T~~threshold runoff values were computed for effective rainfall durations of 1-hour in the 200 selected sub-basins by using Manning equation and GIUH method as mentioned in section 2.2. 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. In ~~Addition~~additional~~ly~~, 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 threshold runoff~~TR~~ and the soil moisture deficit, ~~are~~ differ~~ent~~ by~~ at different~~ location~~s~~. 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 timing~~mes~~ of the 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~~9) 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:

$$P = 85.02 - 14.39 ln(A) \qquad (~~8~~9)$$

~~where~~ 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; 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 the 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 km^2, between 40 and 100 km^2, and greater than 100 km^2, respectively.

4.4 Validation

For the validation of the performance of the P-A curve, the quantitative flash flood criteria for actual flash flood events were applied. This experiment assumed the gauged mean areal precipitation as a prediction. The experiments were assessed whether the prediction exceeded the quantitative flash flood criterion when an actual flash flood event occurred in the basins. If the prediction exceeded the quantitative flash flood criterion, a flash flood warning would be issued. According to the results, the flash flood occurrence was captured for 9 out of 12 events when the criteria were evaluated (Table 4). Figure 11 shows a~~the~~ detailed interpretation of the proposed ~~QFFC~~ criteria obtained from the P-A curve ~~were validated~~ for the four selected actual flash flood events ~~observed~~ in the Myungji, Soohang, Sanasa and Danjigol valleys in 2005, 2006, 2007 and 2009. ~~Figure 11 shows t~~The 1-hr MAP and 1-hr criteria~~QFFC~~ in the selected sub-basins with different areas were provided in the figures. The estimated values of 1-hr criteria~~QFFC~~ were 31.9 mm, 37.2 mm, 37.7 mm and 31.7 mm for sub-basins area of 40.1 km^2, 27.8 km^2, 26.8 km^2, and 40.6 km^2, respectively. The 1-hr MAP exceeded the 1-hr criteria~~QFFC~~ during the first three actual events, but the 1-hr MAP at Danjigol valley in 2009 event did not exceed the 1-hr criteria~~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.~~ Th~~i~~ese results suggest~~s~~ that the proposed ~~QFFC~~ criteria 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 Discussion

5.1 Uncertainty of flash flood forecasting method

There are many flash flood forecasting methods. The methods can be divided into three categories: flow comparison methods, rainfall comparison methods, and flash flood susceptibility assessment. The proposed P-A curve is rainfall threshold that included with the rainfall comparison methods like FFG. The rainfall comparison method is a popular tool for warning about flash floods, and this method is commonly used for flash flood forecasting. However, the previous rainfall threshold method has some limitations, recent studies tried to improve warning accuracy by using distributed physical hydrological modeling (Kobold and Brilly, 2006; Reed et al., 2007; Norbiato et al., 2009). Hapuarachchi and Wang (2008) suggested that physically based distributed hydrological models are more appropriate than data-driven models and conceptual hydrological models for flash flood forecasting. However, the most important thing of flash flood forecasting is a providing the warning information to decision makers or citizens with relatively simple, clear, and immediate. It means that not only the sophistication but also promptness with reasonable accuracy also is necessary for flash flood forecasting. In this respect, this study proposed quantitative criteria using P-A curve for flash flood warning based on FFG. The key advantage of this method is that it doesn't need any further calculation compared to the other rainfall comparison method. In other word, the proposed criteria and methodology will serve as an important tool for issuing flash flood warnings based on only rainfall information.

However, this study has some assumptions and limitations. The P-A curve is based on the FFG, not real observed flash flood events because there is lack of observed flash flood events. In addition, the proposed P-A curve has some uncertainties from lots of sources such as soil moisture estimation (SURR), Threshold runoff estimation method, finding the optimal P-A curve by using ROC method, collection of actual flash flood events etc. But, these problems are not confined to this study because the phenomena triggering flash flood are very complex. Any flash flood forecast method has also large uncertainties due to input data errors, and modelling errors. Thus, it is necessary for understanding of the uncertainty from all these sources for decision making in flood warning because good uncertainty estimates of flash flood forecasts can add credibility to the forecast system.

5.2 Utilization of a P-A curve for flash flood forecasting

Some flood forecasting systems have been developed and operated in some countries (Mogil et al., 1978; Sweeney, 1982; Mason, 1982; Alfieri et al., 2012). Northern America has a flash flood forecasting system using gridded flash flood guidance (GFFG). This system uses multi-sensor precipitation estimates and forecasts based on NEXRAD (Next Generation Weather Radar), rain gauges and NWP (numerical weather prediction) model outputs. The European Flood Forecasting System (EFFS) used the LISFLOOD-FF for generating river flow and LISFLOOD-FP to model the overbank flows and inundation areas, and they use gauged rainfall, radar rainfall, and NWP model outputs (Roo et al., 2003). ALERT in Australia uses a hydrological model with real-time rainfall and water level data. They also assess the severity of flooding using simple manual guides (look-up tables). Thus, the ideal flash flood system needs to combine two approaches. It must present the criteria used to judge flash floods in an intuitive way for very short-term flash floods (less than 1 hour). It must also make predictions with sophisticated modeling using a physical distributed model for flash floods with greater than a 3-hour duration. Therefore, the FFGC (flash flood guidance criteria) are used for short-term flash floods.

This study focused on using a P-A curve, and it assessed the outcome when using only gauged rainfall data. However, the quality of flash flood forecasting depends on the quality of the rainfall data. Additionally, reliable rainfall forecasts with adequate lead-time and accuracy are essential for flash flood forecasting. In general, the gauged rainfall, radar data (Sinclair and Pegram, 2005; Mazzetti and Todini, 2009), and satellite data (Sorooshian et al., 2000; Kubota et al., 2007) have been used for quantitative precipitation estimates (QPEs), and some studies have used multiple precipitation sources (Sokol, 2006; Chiang et al., 2007). Therefore, this method is necessary for assessing the applicability of using rainfall data obtained from various sources.

6~~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~~ it could be effectively estimated as a function of the corresponding sub-basin area. These results mean that the threshold for 1-hr flash flood prediction can be classified according to 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 with less than1-hr duration are frequently occurred. However, flash flood with more than a ~~2~~3-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 (less than 1 hr) and long-duration (greater than 3 hrs) is necessary for managing flash flood efficiently.

Acknowledgements

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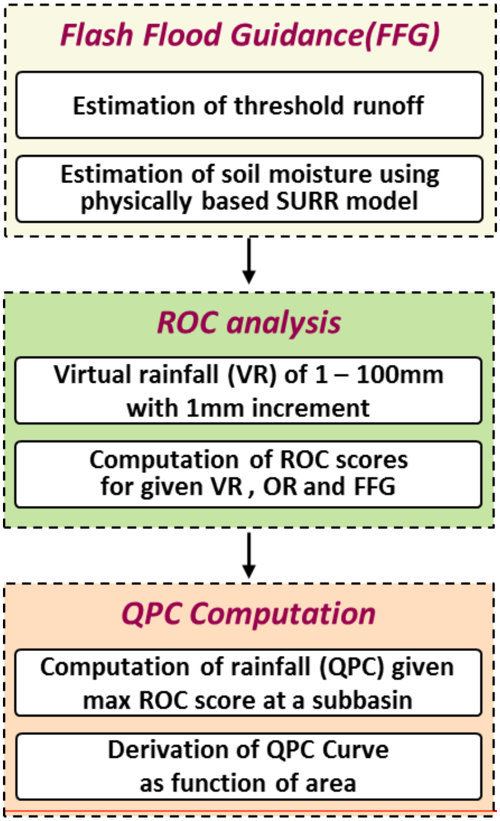


Figure 1: Overall methodology used to estimate the quantitative precipitation criteria.

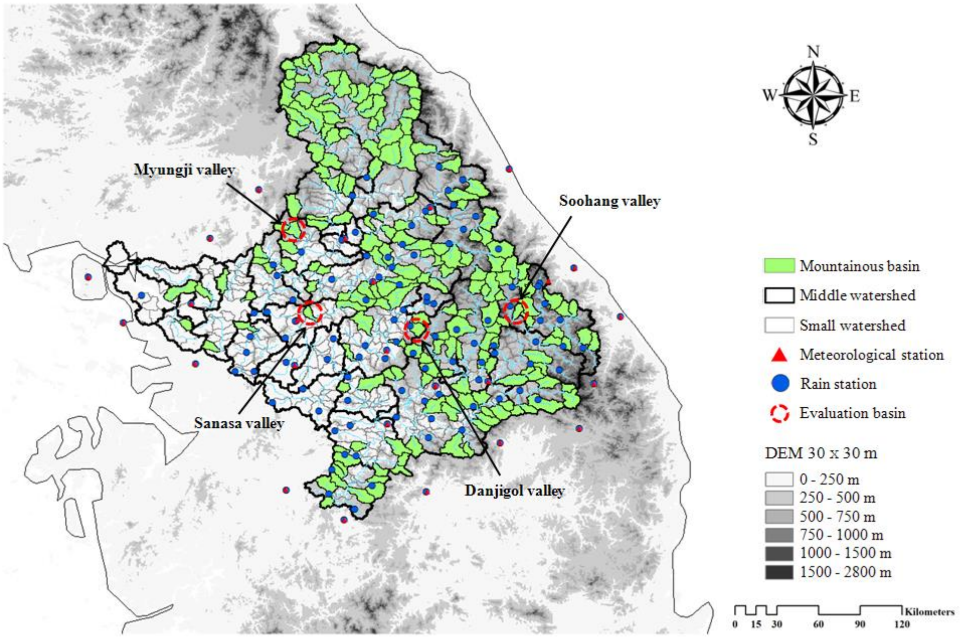
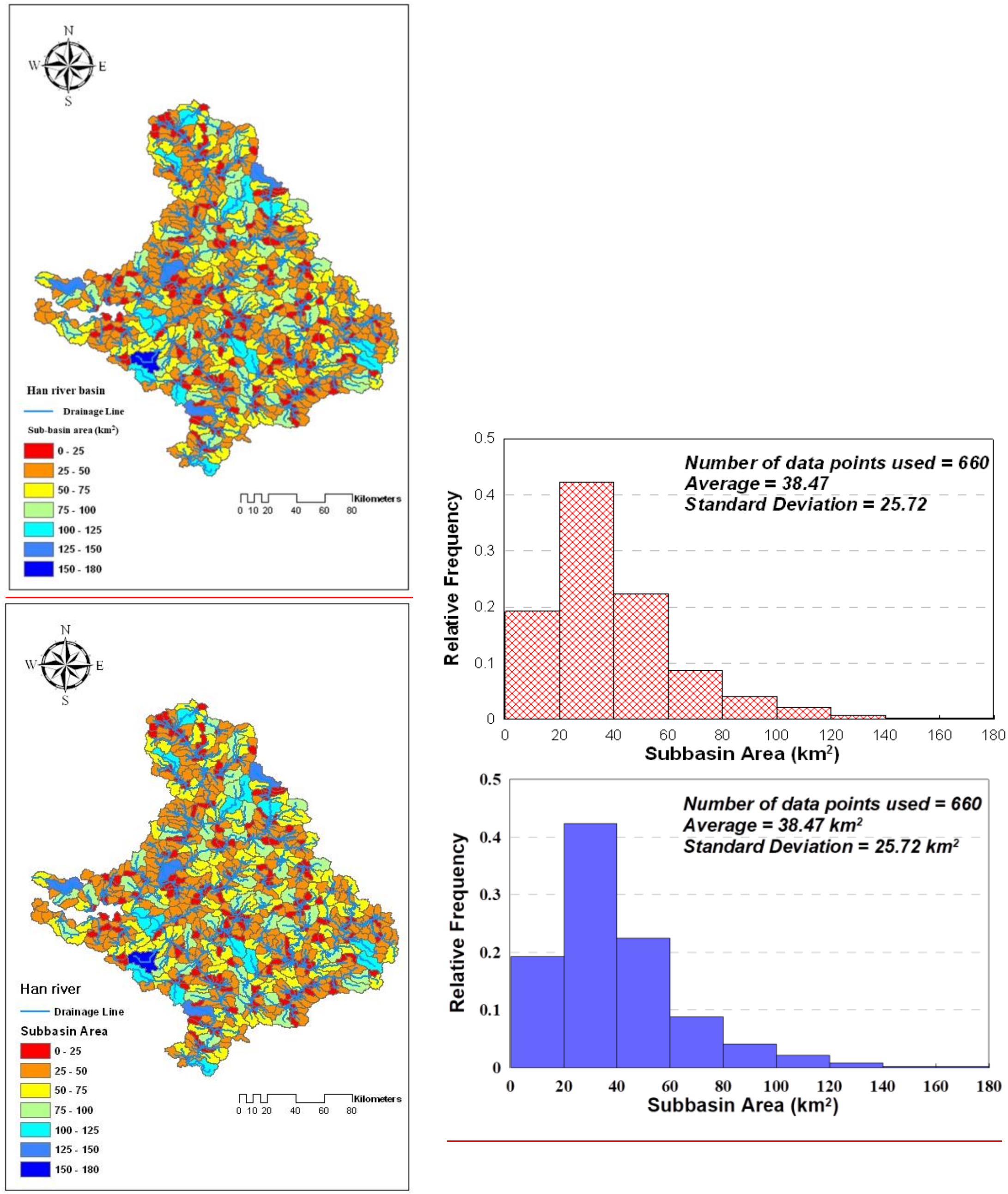
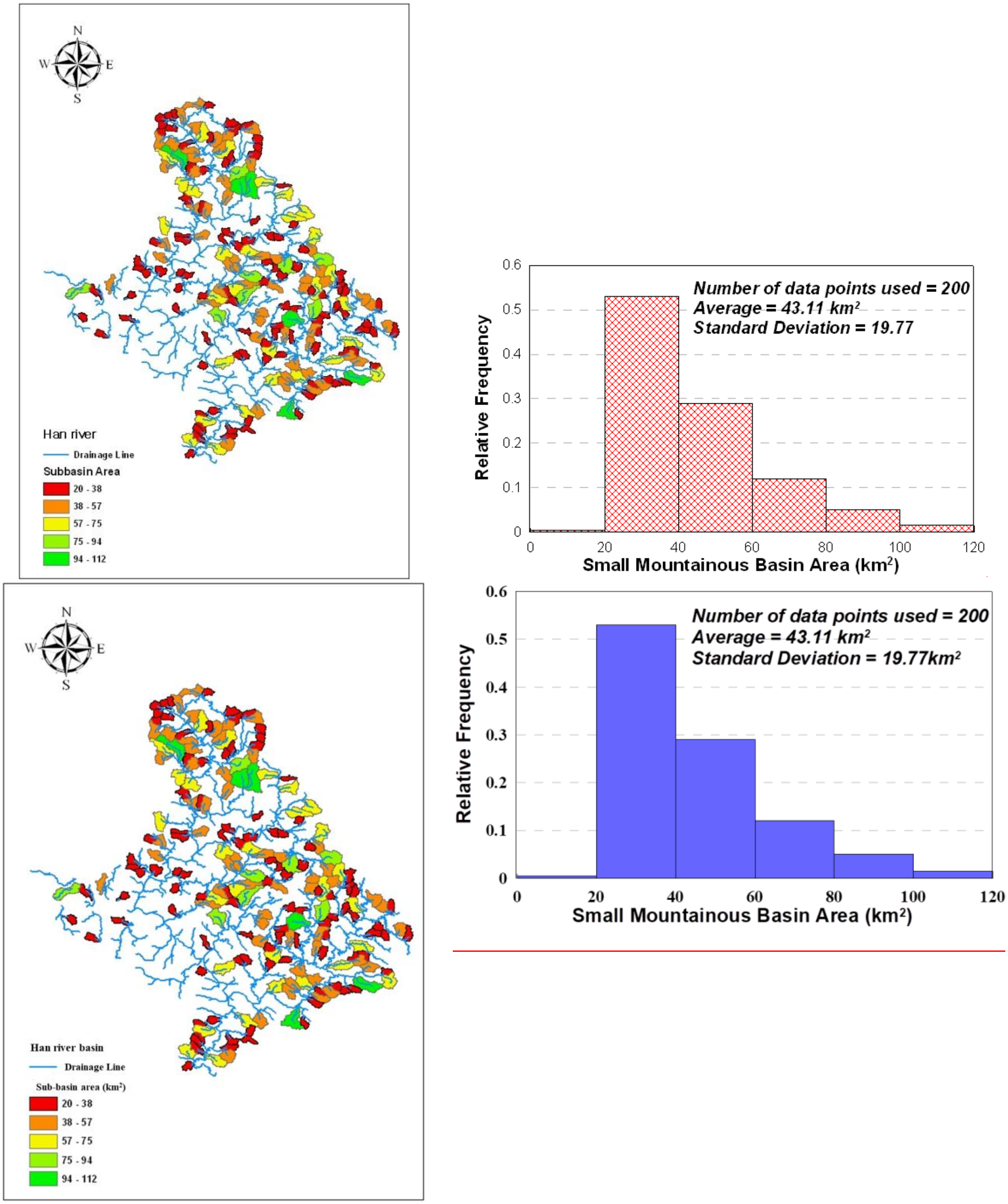


Figure ~~2~~1: Study area.



(a) (b)

Figure ~~3~~2: (a) ~~(a)~~ 660 sub-basins in the Han River basin and (b) ~~(b)~~ their relative frequency of their areas.



(a) **(b)**

Figure 43: (a) Selected 200 sub-basins in the Han River basin and (b) (b) the relative frequency of their areas.

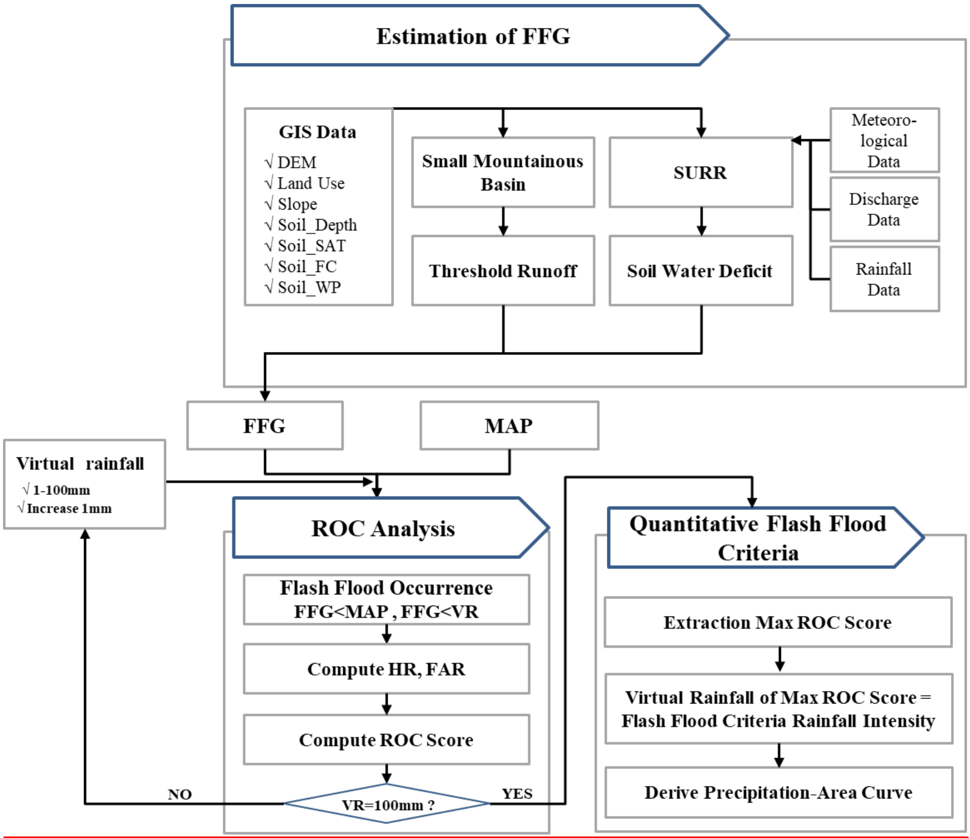
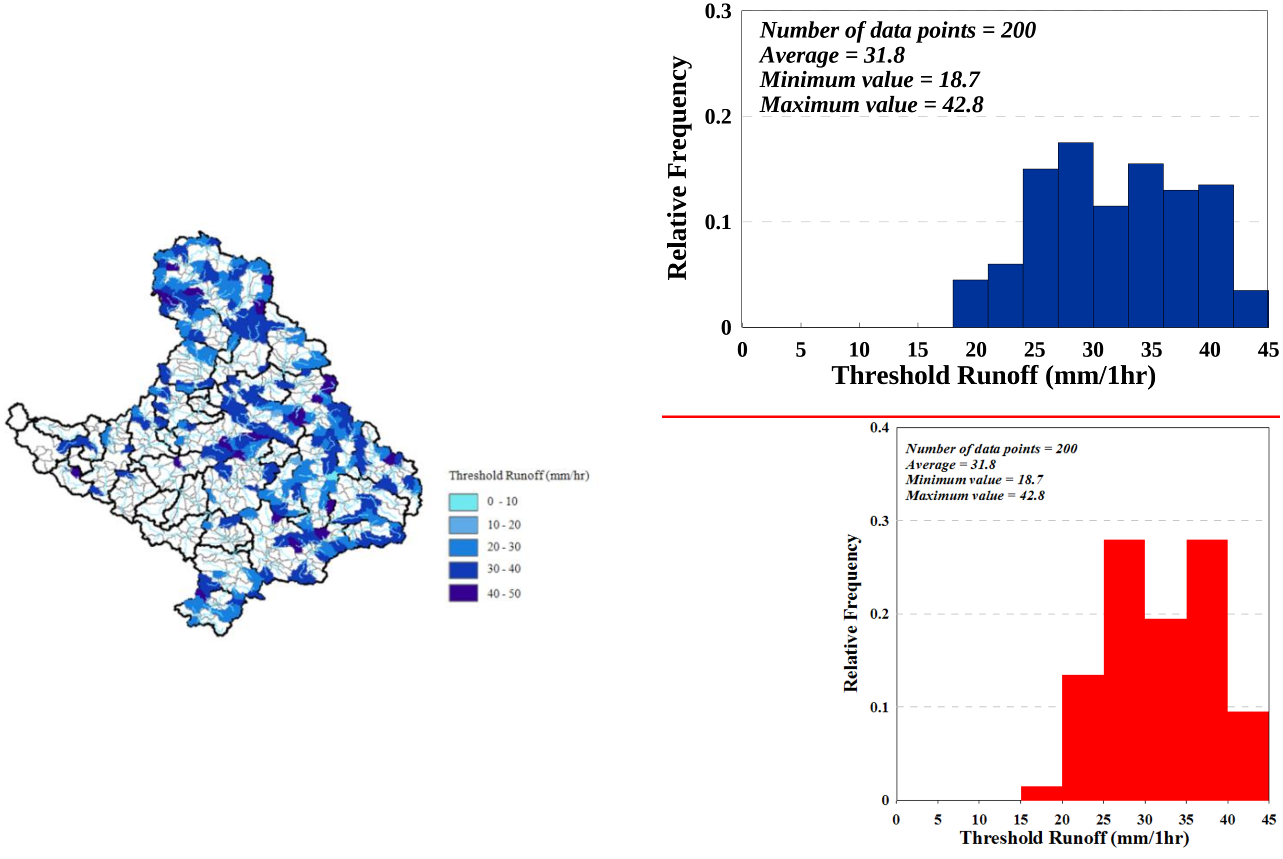


Figure 4: Overall methodology used to estimate the quantitative precipitation criteria.



(a) (b)

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

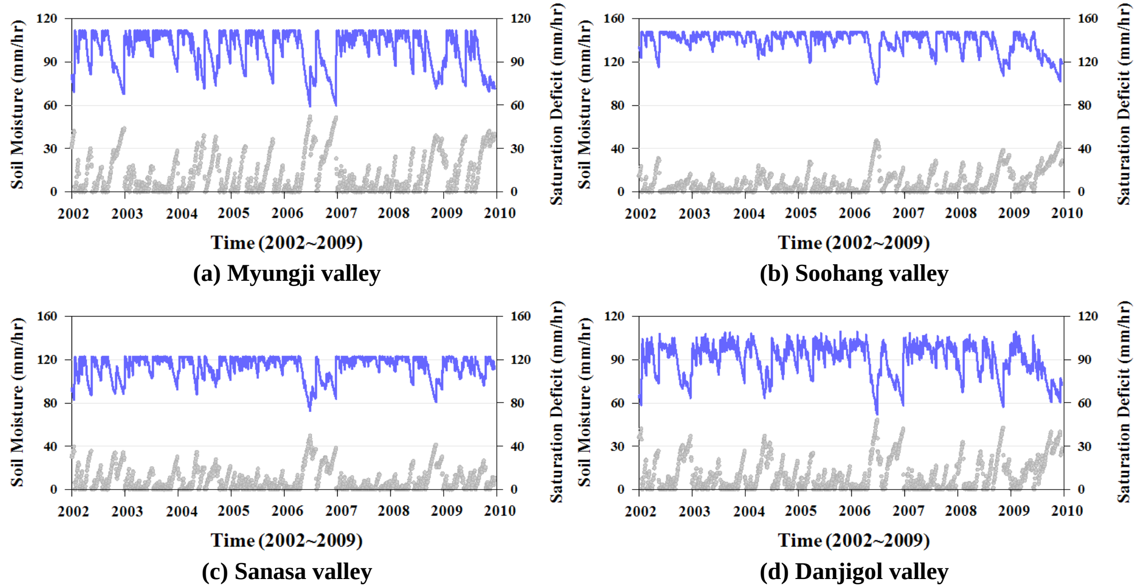
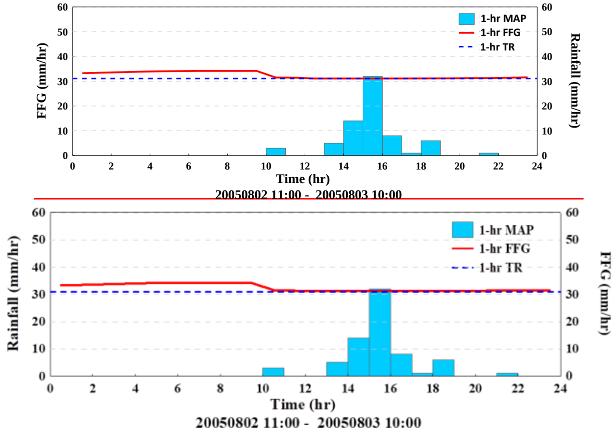
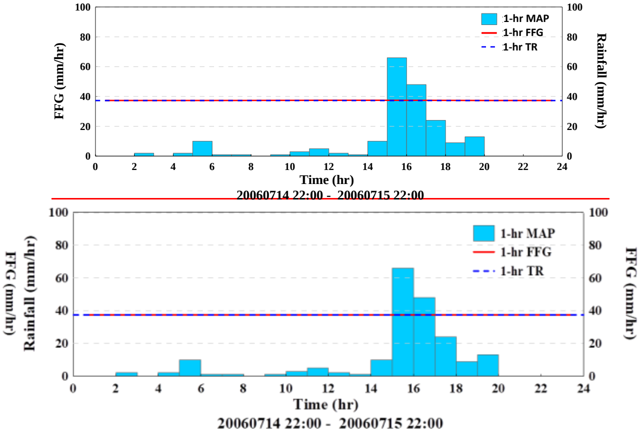
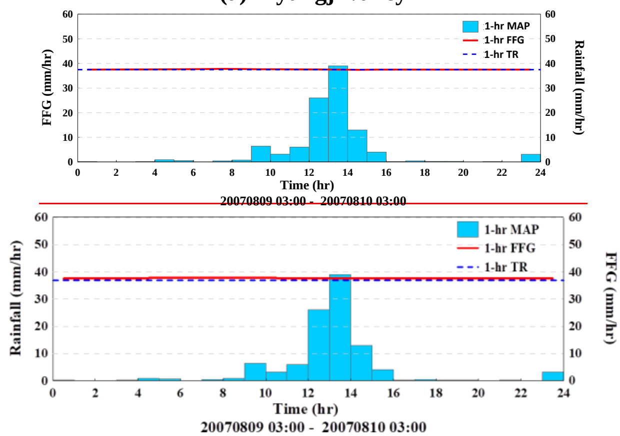


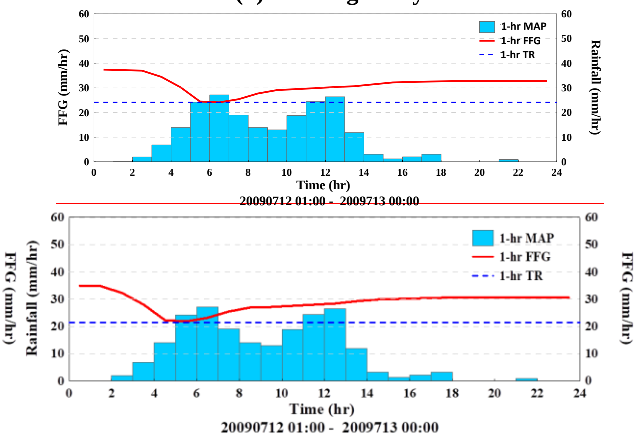
Figure 6: Soil moisture and soil moisture deficit in selected sub-basins. The blue and grey lines represent soil moisture, and saturation deficit, respectively.





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





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

Figure 7: Threshold runoff (TR), Mean areal precipitation (MAP) and estimated FFG (Flash Flood Guidance) for selected flash flood events.

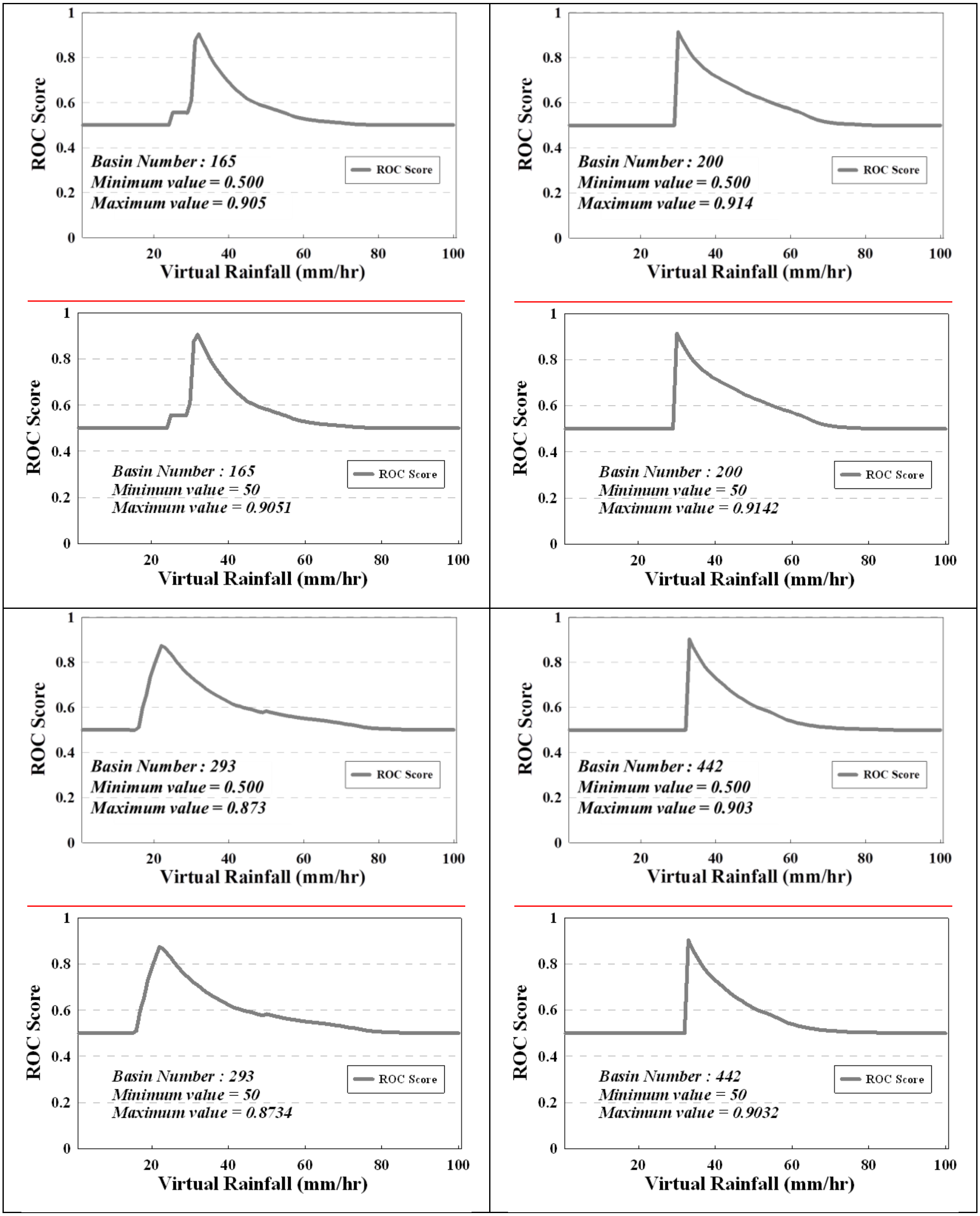


Figure 8: ROC score estimated for selected sub-basins using virtual rainfalls of 1–100 mm/h.

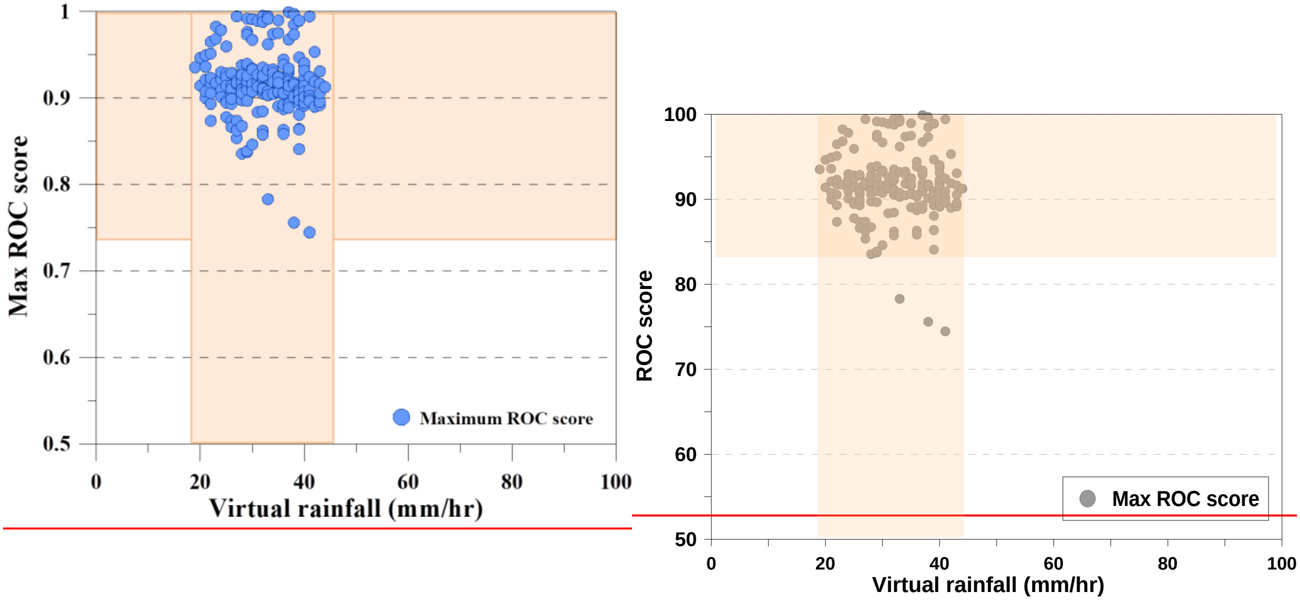


Figure 9: Relationship between maximum ROC and uniform virtual rainfall for all the sub-basins. Shaded areas represent the range (maximum to minimum) of virtual rainfall and ROC score.

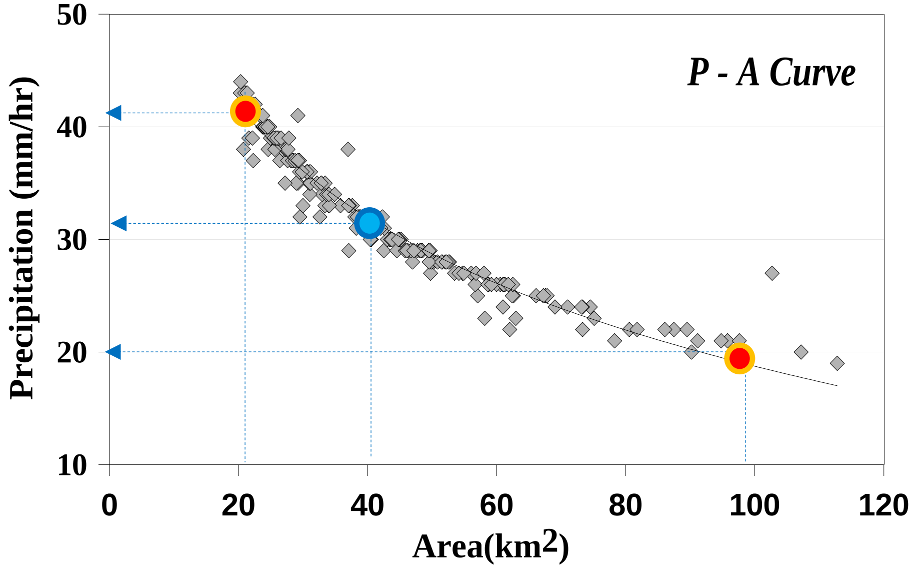
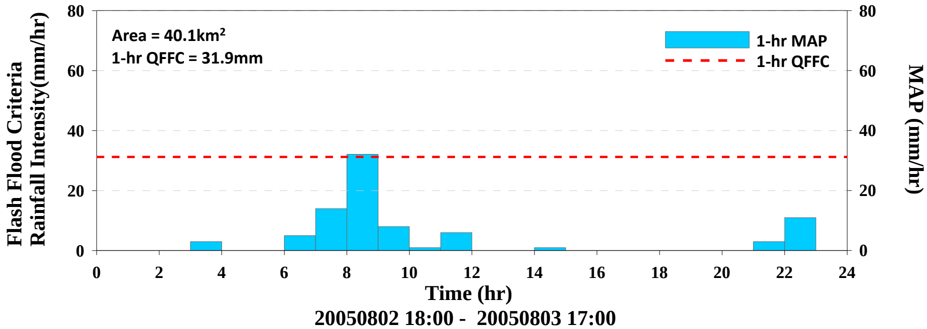
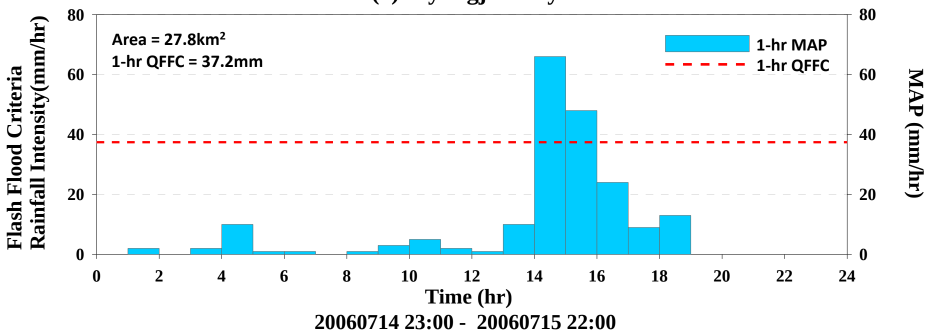


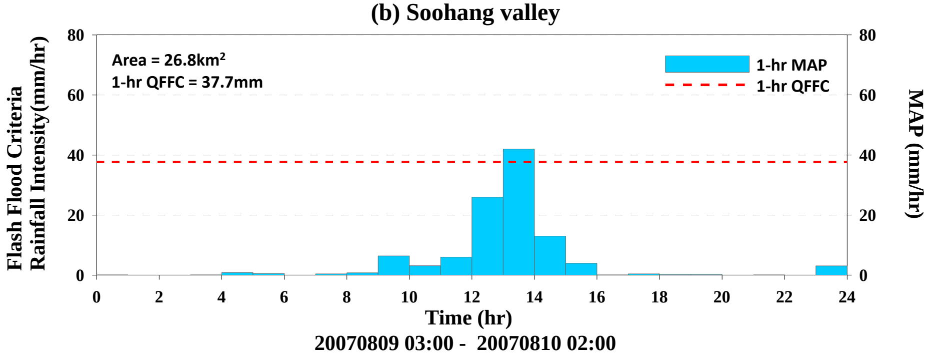
Figure 10: Derived QPC curve for quantitative flash flood conditions ~~(QFFC).~~ Circles represent the categories of criteria according to basin area



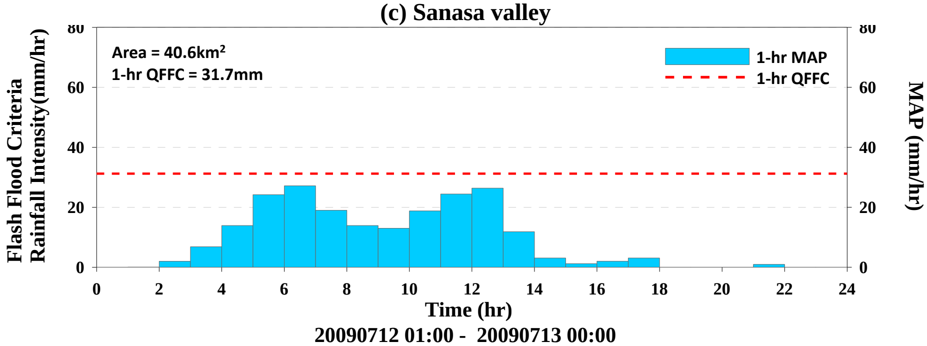
(a) Myungji valley



(b) Soohang valley



(c) Sanasa valley



(d) Danjigol valley

Figure 11: Validation of quantitative flash flood criteria.

Table 21: 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

Table ~~1~~2: ROC ~~score~~ analysis 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

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]

Table 4. Validation of FFGC using observed flash flood cases

S.No.	Time	Area (km^2)	MAP (mm/hr)	FFGC (mm/hr)	FF occurrence using FFGC
1	2005.08.03 02:00	40.1	32.1	31.9	○
2	2006.07.14 13:00	27.8	66.0	37.2	○
3	2007.08.09 16:00	26.8	42.0	37.7	○
4	2009.07.12 06:00	40.6	27.2	31.7	x
5	2010.09.11 19:00	44.9	37.0	30.3	○
6	2011.07.27 05:00	37.0	57.5	33.1	○
7	2011.07.26 17:00	47.0	49.2	29.6	○
8	2011.07.27 08:00	34.0	52.1	34.3	○
9	2011.08.03 12:00	37.6	38.1	32.8	○
10	2011.08.09 13:00	61.0	22.1	25.9	x
11	2011.08.14 13:00	40.5	23.2	31.8	x
12	2012.07.15 08:00	90.2	21.5	20.2	○