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EVIDENCE AND IMPLICATIONS OF NONLINEAR FLOOD RESPONSE IN A SMALL MOUNTAINOUS WATERSHED

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ABSTRACT

This study investigates the impact of event characteristics on runoff dynamics during extreme flood events observed in a 8.5 km^2 experimental watershed located in South Korea. A high-quality dataset containing the 31 most extreme flood events with event rainfall in excess of 50 mm were analysed using an event-based rainfall-runoff model; the Revitalised Flood Hydrograph (ReFH) routinely used for design flood estimation in the United Kingdom. The ReFH model was fitted to each event in turn, and links were investigated between each of the two model parameters controlling runoff volume and response time, respectively, and event characteristics such as rainfall depth, duration, intensity and also antecedent soil moisture. The results show no link between the parameter controlling runoff volume and any of the event characteristics, but identified a dependence between response time and rainfall depth. These results show that the linear unit hydrograph fails to adequately represent a reduction in watershed response time observed for the more extreme events. A new and dynamic link between the unit hydrograph shape and rainfall depth is introduced. The consequence of the observed nonlinearity in response time is to increase design peak flow by between 50% for a 10 year return period, and up to 80% when considering the probable maximum flood (PMF).

Keywords: flood event modelling, non-linearity, design floods, Probable maximum flood

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INTRODUCTION

Event-based rainfall-runoff models play an important role in applied engineering hydrology, especially for estimating design floods in small and ungauged watersheds, especially where an entire design flood hydrograph is required rather than just a design peak flow value (Kang et al. 2013). These type of models are most often based on lumped conceptual representations of the runoff generating processes where the runoff volume derived from a large storm event can be estimated using only a few parameters. The excess water is then routed to the watershed outlet using a standardised unit hydrograph, and finally a baseflow component is added (Pilgrim et al. 1992). Examples of event-based rainfall-runoff models used in engineering design include: the Australian rainfall-runoff model (IOEA 2001), the SCS curve number method (Hawkins et al. 2009) used in the USA and elsewhere (e.g. Stewart et al. 2011; Jung and Moon 2001; Smithers 2012; Banasik et al. 2014) and the Revitalised Flood Hydrograph (ReFH) model used in the UK (Kjeldsen 2007; Faulkner and Barber 2009) and also tested in South Korea (Joo et al. 2014). In a review of the SCS curve number model, Ponce and Hawkins (1996) cited the: *simplicity, predictability, stability, parameter parsimoniousness, and responsiveness to key factors controlling runoff, such as soil and climate as reasons for the popularity of the curve number method.* It is reasonable to assume that the same reasons can explain the widespread use of event-based methods more generally in engineering hydrology. Unit-hydrograph based models used in practice typically assume that the watershed response to effective rainfall is linear and invariant to the magnitude of the event. However, empirical evidence and model based simulations have been published by several researchers suggesting that flood event data exhibit a non-linear behaviour (e.g. Szilagyi 2007). Studying the effect of event magnitude on unit hydrograph parameters, Kokkonen et al. (2004) reported evidence of a relationship between event magnitude and response time in the data from two small experimental watershed ($<$1 km^2), but found no evidence of such relationship on two larger watersheds (58 km^2 and 1125 km^2). They also found the non-linear effects to be decreasing when using coarser aggregates (more than 1 hour) of the data. Investigating the non-linearity of runoff production and river routing using continuous records from three upland watersheds in the UK, McIntyre (2013) found stronger evidence than expected of non-linearity in routing, and comparatively less evidence in runoff production. Grimaldi et al. (2012) reported a link between time of concentration (watershed response time) and the magnitude (return period) of events in four small to medium sized watershed in Texas. However, when using an event-based method for design flood estimation, the peak flow is not known a-priori as this is in fact the required outcome of the analysis. For operational purposes it is therefore more useful to try and relate the change in watershed lag-time to the characteristics of the rainfall event which will typically be available from an existing intensity-duration-frequency (IDF) curve.

The existence of non-linearity in the watershed response during large flood events can potentially have serious implication for design flood estimation. With reference to the rational method, (Efstratiadis et al. 2014) highlighted the use of constant values of lag time as a serious flaw in most design flood estimation methods. Most conceptual models are calibrated on a selection of observed flood events which, in practice, is likely to contain only a limited number of very large events. In a review of selected flash flood events from the United Kingdom, Archer and Fowler (2015) argue that the response time observed during very intense rainfall events (flash floods) is different from the response time of more average events. However, the models are frequently used for estimating design event for return periods from 100 years, up to 10,000 years and even probable maximum floods (PMP) in the case of reservoir safety. An example of such engineering practice includes simulation of the probable maximum flood in the United Kingdom, where the Flood Studies Report (NERC 1975) recommended reducing the Time to peak (Tp) of a standard triangular unit hydrograph to a value of 67% of the mean value obtained by analysing all events. This will not affect the runoff volume, but will result in an increase in the simulated peak flow value. The objective of this study is to investigate the extent of non-linearity in the largest flood events recorded in a small and mountainous experimental watershed (8.5 km^2) located in South Korea. This objective will be achieved by first conducting an exploratory analysis on the raw data followed by an investigation of how critical parameters of a conceptual event-based rainfall-runoff model (the ReFH model) vary with event characteristics. The implication of the identified non-linearity in flood response is discussed with reference to design flood estimation. The strategy adopted in this study is to use the ReFH model as a hypothesis testing tool, by first applying a (linear) model to analyse observed flood events, and then subsequently investigate where the model assumptions are not adequately representing the behaviour of the observed events. Thus, it is not the objective to demonstrate that the model performs well, but rather to identify aspects that are not well captured by the linear model structure, and propose corrections to address these.

THE SEOLMA-CHEON WATERSHED

The data used in study consist of hourly rainfall and streamflow measurements from the experiment watershed, the Seolma-Cheon, operated by the Korean Institute of Civil Engineering and Building Technology (KICT) since 1996. The watershed is small and mountainous, and it is located north of Seoul (Figure 1) on a tributary of the Imjin river forming the border between North and South Korea. The watershed area is 8.5 km^2 and the length of main stream is 5.59 km. As the landscape of the Korean peninsula is dominated by mountain ranges, this type of small and steep watersheds are very common and found through-out the country.

Continuous collection of a number of hydrological variables is in place through an extensive monitoring programme operated by KICT, including: rainfall, climate, flow discharge, sedimentation, water quality, soil moisture, and groundwater. The rainfall is measured at six gauging stations and discharge data are gathering from two stations. From the continuous flow record spanning the period 1996-2012, a total of 41 individual events were identified at the most downstream gauge for which the event rainfall exceeded a total of 50 mm and where, at least, two years of antecedent daily rainfall data were available. Further quality control consisting of a visual inspection of each event and comparing rainfall and runoff volumes lead to the exclusion of a further ten events. Thus the final data set consists of 31 large flood events; a summary is shown in Table 1. The largest event recorded was 571.8 mm in 90 hours on the 26-June-2011 during Typhoon Meari. All observed events were recorded in the period May to September, which in Korea is the hot and humid season. A previous analysis of the rainfall data (KICT 2010) showed that the spatial correlation coefficient between rainfall observed at the six different raingauges vary between 0.96-0.99. It was therefore concluded that the rainfall observed over this relatively small watershed during very large events can be considered as being homogeneous for the purpose of this study.

Due to the complexity of real observations, not all events represent a singular rainfall input followed by a well-defined and single peaked flow response. This is not a problem when studying the ratio between rainfall and runoff volumes (percentage runoff), but might cause problems when using purely data-based measures of lag-time. Also, the durations of the real events used in the exploratory study are considerably longer than the critical duration of the watershed. Consequently, the study will use the total volume of the event-generating rainfall when exploring runoff volume, but only the rainfall falling between the start of the event-generating rainfall and the subsequent peak of the response hydrograph when studying watershed response times.

Together with rainfall data, evapo-transpiration data are used to model the long-term water balance needed for assessing the antecedent soil moisture content (or initial soil moisture) at the onset of each event.

THE REVITALISED FLOOD HYDROGRAPH (REFH) MODEL

The Revitalised Flood Hydrograph (ReFH) model was developed for design flood estimation in the United Kingdom (Kjeldsen 2007), and it has effectively replaced an outdated model published as part of the UK Flood Studies Report (NERC 1975) for most practical uses where a design hydrograph is required. The model has also been successfully used to analyse observed flood events in South Korean watersheds (Kim et al. 2013; Joo et al. 2014). In particular, Joo et al. (2014) found that the performance of the ReFH model was comparable to that of the HEC-HMS model when applied to two Korean watersheds. Details of the model structure, calibration, and design flood simulation procedures are provided by (Kjeldsen 2007) and only a short summary is provided here. In common with most other event-based rainfall-runoff models, the ReFH model structure consists of a loss model, a routing model, and a baseflow model, and the links between the three model components are shown in Figure 2. When used for analysing observed events, as in the first part of this study, an additional simple soil moisture accounting model is evoked to provide the soil moisture content at the onset of each flood events.

ReFH Loss model

The purpose of the loss model is to derive the direct runoff excess rainfall resulting from a specific combination of rainfall and antecedent soil moisture. The ReFH loss model is based on a probability distributed model (Moore 2007) where soil moisture storage, C, is assumed to follow a uniform distribution. By neglecting evaporation and drainage into deep soils, the ratio between rainfall, P, and direct runoff (i.e. routed excess rainfall), q, volumes over a storm event is given as

$$\frac{q}{P} = \frac{C_{ini}}{C_{max}} + \frac{P}{2C_{max}} \tag{1}$$

where C_{max} is a model parameter and C_{ini} represent the initial (or antecedent) soil moisture content at the onset of the flood event. The parameter C_{max} is constant for all events and describes the maximum volumetric capacity of the watershed soils. In contract C_{ini} is a dynamic boundary condition that varies between and within events. The ratio between q and P is termed percentage runoff (PR), and the ratio between C_{ini} and C_{max} is used as an index of the antecedent soil moisture. The ReFH loss model in Eq.(1) is used sequentially updating the initial soil moisture C_{ini} at the end of each time step by a simple mass balance $C(t) = C(t-1) + P(t)$, but the model can also be used over the aggregate of an event to estimate the total runoff volume from a rainfall event, analogue to how the curve number method works. A key feature of the ReFH loss model in Eq.(1) is that, in contrast to the curve number model, antecedent soil moisture is explicitly included into the calculation of runoff volume via C_{ini}. The initial soil moisture, C_{ini}, for each event is estimated using a simple soil moisture accounting model driven by daily precipitation and potential evaporation data. This model is used to calculate the development of soil moisture for a period of up-to two years prior to each individual event, and assuming that soil moisture is at field capacity at the start of this period. More details of the structure and application of this model is provided by Kjeldsen (2007).

Routing model

The ReFH model uses a kinked triangular instantaneous unit hydrograph (IUH), see Figure 3, to route the excess rainfall to the watershed outlet, thereby creating a hydrograph of direct runoff (or routed excess rainfall). The IUH has a single parameter, the time to peak (Tp) and the ReFH model uses the S-curve method to derive a unit hydrograph for the selected time step. In the current form, the shape of the IUH is invariant to the storm severity, thus potentially neglecting important non-linear behaviour of storm runoff dynamics. This issue will be investigated further in this study.

Baseflow model

The ReFH baseflow model is based on a linear reservoir with a lag coefficient denoted BL and with recharge into the reservoir linked directly to the direct runoff and controlled by a recharge parameters (BR). The resulting recursive baseflow model formulation is given as

$$z_t = k_1 q_t + k_2 q_{t-1} + k_3 z_{t-1} \tag{2}$$

where q_t and z_t represent direct runoff and baseflow, respectively, and k_1, k_2 and k_3 are model parameters that are themselves functions of the baseflow lag (BL) and the recharge coefficient (BR). The two parameters BL and BR are considered the model parameters in need of calibration.

Total flow

Finally, the total flow, Q_t is calculated as the sum of the routed excess runoff (direct runoff), q_t and the baseflow z_t, i.e. $Q_t = q_t + z_t$.

Model calibration

Calibration of the ReFH model is implemented as a two-stage procedure. First the two baseflow parameters (BL and BR) are estimated for each individual event followed by joint optimisation of the loss model and routing model parameters C_{max} and Tp. The ReFH baseflow model was developed specifically to enable the two baseflow parameters BL and BR to be estimated directly from the recession curves of the observed hydrographs, thereby reducing the number of parameters that must be calibrated via optimization to two (C_{max} and Tp). To estimate BL and BR for an event it is necessary to provide the initial runoff which is the first flow value for each event. Next, the end of direct runoff and a point further down the recession curve are determined and the two baseflow parameters BL and BR are optimised to provide the best possible fit to the hydrograph recession. More details on the baseflow calibration procedure is provided by (Kjeldsen 2007). It is assumed here that the parameters BL and BR are constants and that variation between events is a consequence of sampling variability. Thus, a set of representative values of BL and BR was derived by averaging over the values obtained for each of the events. Next, the two parameters C_{max} and Tp are estimated for each event by finding the set of parameter values that minimizes the squared difference between observed and simulated runoff, the sum of squared errors (SSE) defined as

$$SSE = \sum_{t=0}^{n} \left(Q_{t,obs} - Q_{t,sim}\right)^2 \tag{3}$$

where n is the number of flow values for the considered events. This process will provide a set of parameter values of C_{max} and Tp for each individual event. An alternative procedure could base the model calibration on values of SSE calculated by considering all events simultaneously. This would give only one set of parameter values which would represent the best overall fit to the observed events. Joo et al. (2014) found that the simultaneous calibration can give a slightly superior parameter estimates when compared to a set of parameters derived as the averages over values calibrated for each event. However, as the objective of this study is to investigate performance of the model for different types of events, the procedure adopted in this study was to calibrate the ReFH model for each event in turn.

RESULTS

The 37 large flood events were analysed to investigate if runoff volume and watershed response time vary with event characteristics in a manner which is not captured by the structure of the ReFH model as described in the section above. The analysis was conducted in two steps. First, an exploratory analysis was performed to investigate if links between event characteristics and the characteristics of the runoff events (percentage runoff and lag time) can be identified. The exploratory analysis will focus on characteristics of the observed events (percentage runoff and response-time), but will evoke aspects of the ReFH baseflow and soil moisture accounting model to separate total flow and baseflow, and to calculate the initial soil moisture content at the onset of each event. Secondly, the ReFH model is fitted to each of the events in turn, and links between rainfall characteristics and the resulting model parameters (C_{max} and Tp) are investigated to identify potential structural limitations of the ReFH model formulation. In contrast to the exploratory analysis, focussing on the ReFH model parameters directly will provide a more robust representation of how percentage runoff and response time vary with event characteristics.

Exploratory analysis: Event characteristics

First, baseflow is separated from the total flow so that total flow is divided into a baseflow and a direct runoff component. This step is necessary to ensure that each event is considered in isolation and that the influence of elevated flow from pre-event rainfall is minimised. Next, the impact of initial soil moisture on the observed runoff volume is investigated, focussing on the ratio between volume of direct runoff and the associated volume of total rainfall, i.e. percentage runoff (PR). Finally, the influence of event characteristics on watershed lag times is investigated.

Separation of baseflow

The ReFH baseflow model was fitted directly to each of the flood events, and the two baseflow parameters BL and BR estimates for each event. An example of the baseflow model fitted to an observed event is shown in Figure 4. For most events the volume of baseflow is small compared to the total runoff volume. However, for some of the selected events the initial flow is elevated as a result of large rainfall input in the period before the event (see example in Figure 5). In such cases it is clearly important to remove the baseflow contribution to avoid the mass balance over the duration of the event to be too distorted, e.g. estimating runoff volumes in excess of 100% of the rainfall. The average parameter values considering all 31 events are $BL = 58.4$ hours and $BR = 1.31$ (dimensionless). Using these average parameter values, the direct runoff volume was derived for each of the 31 events by subtracting the estimated baseflow from the total flow, and percentage runoff estimated (PR) for each event as the ratio between direct runoff and total rainfall volumes.

Influence of initial soil moisture on runoff production

It is generally accepted that percentage runoff (PR) is closely related to antecedent wetness (Ponce and Hawkins 1996), especially for watersheds where runoff production is dominated by saturation excess processes. Figure 6 shows the estimated PR plotted against the initial soil moisture content, C_{ini} (as estimated from the ReFH model), at the onset of each of the 31 events. The plot shows that the ratio between rainfall and runoff volume (i.e. PR) for each event depends strongly on the soil moisture content at the onset of the event, even if there is a large degree of variation within the data. The plot in Figure 6 shows that even for a steep mountainous watershed such as the Seolma-Cheon it is important that the rainfall-runoff transformation during the most extreme events accounts for the initial soil moisture content. The data in Figure 6 also show that not all events occur when the initial soil moisture content is high. Thus, the adoption of fully saturated soil $(C_{ini} = 1)$ for calculation of design events at more modest return periods might lead to over engineered structures. Note that none of the events in Figure 6 have a C_{ini}/C_{max} ratio of one, i.e. fully saturated. This is partly as a result of the soil moisture calculations, where evaporation and deep drainage is removed from the soil at the end of the time step.

As the ReFH loss model explicitly includes C_{ini} in the prediction of percentage runoff (unlike the SCS model), the results in Figure 6 endorse the use of a loss model with explicit consideration of antecedent soil moisture, even for a steep mountainous watershed with shallow soils, such as the Seolma-Cheon, where runoff during very large events is generally expected to be the result of infiltration excess rather than saturation excess.

It was also investigated if percentage runoff had any relationship to rainfall characteristics such as total rainfall depth, rainfall duration, average rainfall intensity and the maximum one-hour rainfall intensity. However, no visual or statistically significant relationships were identified.

Watershed lag time

Next the link between lag-time and other event characteristics is investigated. The lag-time is defined here as the difference between the centroid of the rainfall occurring prior the peak of the flood event, and the time of the peak itself. In Figure 7 the lag-time for each of the 31 events is plotted against the rainfall depth, duration, average intensity and initial soil moisture, where the rainfall volume and intensity both refer to the occurrence of rain between the onset of the event and the peak of the hydrograph. Of the regression relationships shown in Figure 7 only the relationship between lag-time and and intensity as measured between event onset and flow the peak (lower right panel) can be considered statistically significant from zero at the 5% significance level. This shows that the watershed respond faster to more intense rainfall events. But notably, a subset of the observed lag-times are larger ($>$10 hours) than would normally be expected for a small and steep watershed the like Seolma-Cheon. A closer inspection of the events showed that these lag-times were a result of event where an initial large part of the rainfall falls on dry soils (low C_{ini}/C_{max} ratio) resulting in a relatively muted flow response but a significant wetting of the soil. The actual event peak flow is then a result of subsequent smaller rainfall amount falling on the now much wetter soil. The net effect is that the lag-time (distance between rainfall centroid and peak flow) becomes large. This suggests that care should be taken when using a purely data-driven approach to quantifying response times as it might not result in a useful representation of the runoff dynamics with explicitly considering the antecedent wetness conditions of the watershed.

Exploratory analysis: ReFH model parameter characteristics

The exploratory analysis described above found that runoff volume is closely linked to the antecedent soil moisture, and that watershed lag-time might be linked to rainfall intensity. This would suggest that the ReFH model structure is adequate for describing the runoff production but that the linear unit hydrograph might not provide a good representation of the watershed response during extreme rainfall events. This hypothesis will be further tested in this section by fitting the ReFH model to each individual event in turn, and then investigate if event characteristics have a systematic influence on the model parameters. For each of the 31 flood events the two ReFH model parameters C_{max} and Tp were estimated in turn as described in Section 3.4 using a set of fixed values of BL and BR. The 31 optimised model parameter sets are plotted against selected event characteristics in Figure 8. The strength of the link between each the two ReFH parameters (C_{max} and Tp) and a subset of event characteristics (rainfall depth, initial soil moisture) was investigated using ordinary least squares regression models, linking the ReFH parameters to each event characteristics in turn (including an intercept value). The resulting estimates of R^2, slope of the regression line, and the associated significance levels are shown in Table 2. Note that the correlation coefficient between two model parameters Tp and C_{max} (not shown in the Table) is very close to zero (-0.06) and thus the parameters are not correlated. This was expected as they represent two different parts of the runoff production.

The results in Table 2 show that by explicitly taking into account the antecedent wetness when calculating the direct runoff volume (equation 1), the ReFH model effectively removes the relationship between the C_{max} and event characteristics. Consequently, there appears not to be enough systematic variation in the values of C_{max} between events that a further adjustment of the existing loss model can be achieved based on the available data.

For the Tp parameters a significant relationship is evident between the estimated parameter values and the rainfall characteristics as measured between event onset and the flow peak; in particular the rainfall depth and the average intensity with the former being slightly stronger. This suggests that a fixed unit hydrograph representing an average of the individual events might not be a sufficient representation of runoff dynamics during the most extreme events. Note that the statistical relationship in Figure 8 (upper right panel) between Tp and rainfall depth, a log-transformation was applied to both the Tp values and rainfall depth. In addition, as the events were initially selected based on total rainfall for the entire event being larger than 50 mm, a lower bound was introduced based on the minimum value of observed rainfall between onset of the event and flow peak ($P = 37$ mm). The regression model linking $ln(Tp)$ to $ln(P)$ results in the following relationship:

$$Tp\,(P) = 33.5(P - 37)^{-0.67} \tag{4}$$

The average value of the Tp parameter across the 31 events is 2.43 hours, but once the depth exceeds 87 mm, Eq.(4) predicts that a Tp value smaller than the average value should be used.

The robustness of the relationship in Eq.(4) with regards to outliers and potentially influential events was investigated by calculating Cook's distance D_i for each of the 31 events:

$$D_i = \frac{\sum_{j=1}^{n} \left(\hat{y}_{j(i)} - \hat{y}_j\right)^2}{ps^2} \tag{5}$$

where $\hat{y}_j$ is an estimate of $ln(Tp)$ the j'th event using Eq.(4) and $\hat{y}_{j(i)}$ is the prediction of $ln(Tp)$ for the j event from a refitted version of Eq.(4) for which the i'th observation has been omitted. In the denominator $p = 2$ is the number of fitted parameters in the model, and s^2 is the residual (error) variance of the full model. Generally, influential events have a Cook's distance in excess of $4/n = 4/31 \approx 0.13$. Figure 9 shows Cook's distances plotted against event rainfall. While some spread of values is evident, none of the events has a value in excess of 0.13. In particular, the largest event (rainfall of 436.1 mm) has a relatively modest value. This suggests that the relationship in Eq.(4) can be considered reasonably robust. While not statistically significant at the 5% level, there appears also to be a tendency for observing lower response times if the soil is already wet at the onset of the storm (e.g. high C_{ini} values), but this effect was not studied further here.

Adjusting the parameters of the unit hydrograph based on the known properties of the design rainfall event was suggested by Kundzewicz and Napiórkowski (1986) as a simple way of introducing non-linearity into linear models. However, this method is essentially a black-box method as it does not provide any physical reason why this apparent reduction in response time is observed. The adjustment to the watershed response time in Eq.(4) is based on the observed behaviour of the largest recorded events, so for the purpose of simulating design flood events using design rainfall events of known depth and duration, adjusting the Time-to-peak according to the design rainfall event will result in a simulation of the flood response more consistent with the observed non-linearities.

IMPLICATIONS FOR DESIGN FLOOD ESTIMATION

This section will explore the implications of the identified non-linearity in response time (Time-to-peak) on the resulting design flood estimates generated by combining the ReFH model with design rainfall estimates. The design flood hydrograph can be considered a manifestation of the joint distribution of the antecedent soil moisture and the rainfall events, and the derivation of a design flood therefore requires either a complex analytical solution (Eagleson 1972) or resorting to complex stochastic simulation procedures (Svensson et al. 2013). When using simple design flood models this complex relationship is reduced by combining a design rainfall event (characterised by return-period, depth, duration, and profile) with a representative value of antecedent soil moisture and initial baseflow (Packman and Kidd 1980). Finally, there is often an assumption that the flood with a return period T is a result of the T-year design rainfall event. Thus, to enable the ReFH model to simulate a design flood event for the Seolma-cheon watershed, a number of assumptions are required concerning: initial soil moisture (C_{ini}), initial baseflow (z_0) and design rainfall (depth, duration, temporal profile).

Initial soil moisture

In the previous section it was demonstrated that initial soil moisture (C_{ini}/C_{max}) plays an important role in determining the runoff volume (Figure 6). It is therefore important to pick a value that is sufficiently high to be representative of the conditions expected for a large event. From Figure 6 it is clear that the soil moisture level never reached full saturation for any of the considered events. For this study a reasonably wet soil condition was chosen equivalent to $C_{ini}/C_{max} = 0.75$ which is slightly above the largest observed value in the dataset.

Initial baseflow

Baseflow is not routinely considered for design flood estimation in Korea (MLTM 2012). Also, most of the observed flood events starts from a situation where there is no or very little water in the river. Therefore, an initial baseflow value of zero was chosen. Such a low baseflow value is potentially at odds with an elevated level of initial soil moisture as described above. However, for the purpose of investigating the sensitivity of the design flood hydrograph to non-linearity in response time, this inconsistency is not relevant.

Design rainfall

Selection of a design rainfall event requires specification of: (i) the critical duration, (ii) the required return period (and associated rainfall depth), and (iii) the temporal distribution of the event. Design rainfall estimates for a range of durations and return periods (including PMP) for the Seolma-Cheon watershed were estimated by using the FARD2006 programme (Heo 2007).

The temporal profile of the design flood events was determined using the alternating block method (Chow et al. 1988). The critical depth D_c was first determined by searching across all possible event duration to identify the resulting design flood hydrograph with the highest peak flow value. Assuming a modelling time-step of 0.5 hours and using the average Time-to-peak parameter value of $Tp = 2.50$ hours, the critical duration was estimated to be $D_c = 5.0$ hours.

Sensitivity analysis

A set of design flood hydrographs were simulated using the ReFH model with design input values of: (i) return period, (ii) critical duration, (iii) initial soil moisture and (iv) initial baseflow of zero as discussed above. For each considered return period ($T = 10, 50, 100, 200, 500$, PMP) two design flood hydrographs were estimated using: (i) the average time to peak values $Tp = 2.50$, and (ii) a time-to-peak value adjusted according to the design rainfall amount according to Eq.(4).

Varying only Tp will have an effect on the shape of the design flood hydrograph, and thus peak flow value, but the direct runoff volume remains unaffected. Shorter Tp values signify a faster response, and thus forces the runoff to the catchment outlet faster, which pushes up the peak flow, resulting in steeper hydrographs. Therefore the results in Table 3 below show only the effect of the design rainfall totals on the ratio between the Time-to-peak and peak flow of the design hydrograph as obtained using the non-linear model and the default linear version of ReFH based on an average Tp value.

The results in Table 3 show that the increase in return period will reduce the Time-to-peak parameter as per Eq.(4) and that effect is to increase the steepness of the design hydrograph. The effect is also illustrated in Figure 10 comparing the two design flood hydrographs obtained for a T=100 year return period using an average value of Time-to-peak and a value adjusted according to design rainfall depth as per Eq.(4). Noticeably, the estimated peak flow value for a 100-year design flood event increases by 72% if when the reduction in watershed response time is accounted for.

DISCUSSION AND CONCLUSION

A dataset consisting of the largest 31 flood events observed in the 8.5 km^2 Seolma-Cheon watershed between 1996-2012 has been analysed using an event-based rainfall runoff model. The results show a strong relationship between runoff volume and initial soil moisture in the watershed. This result showss that soil moisture should play an important part in design flood modelling in South Korea, even in upland regions. It was found that the structure of the ReFH loss model, Eq.(1) was capable of representing the effect of initial soil moisture, but once the initial soil moisture was accounted for in the ReFH loss model, no further relationship between runoff volume (C_{max}) and event characteristics (rainfall depth, initial soil moisture) were identified (see Figure 8). Thus, there is no evidence in this dataset to suggest that the ReFH model is an inadequate tool for determining runoff volume for the observed extreme events.

The study also identified a relationship between the watershed response time and the severity of the rainfall event such that the watershed response time becomes shorter when the rainfall depth increases. This effect was found to have important implications when simulating design flood hydrographs. In particular, the peaks of the design flood events were found to increase substantially, especially for larger return periods. The increases were of an order of magnitude (e.g. more than 70% for the 100-year event) and should not be disregarded if such estimates are to be used as the foundation for engineering design such as flood protection and erosion control. If similar effects are identified in other watersheds, then this is likely to have important implications for design flood estimation methods in South Korea where flash floods from small steep mountainous watersheds are common. In particular, if design flood estimates are derived using model parameters representing average conditions then this might result in underestimation of the peak flow of very large events, which could be of strategic importance for design of critical infrastructure such as urban planning, reservoirs and nuclear power installations. It must be emphasised that the investigations undertaken here cannot purport to explain what are the exact hydrological processes responsible for this reduction in response time. Therefore, more detailed field and modelling experiments should be undertaken to identify the geomorphological and hydrological processes controlling runoff during the most extreme events. Also, further research should investigate if similar non-linear effects can be identified in other watersheds from the region. It would be particularly interesting to investigate how nonlinearity is related to watershed characteristics such as: watershed size, slope, soil type, and rainfall regime as this might help to identify ungauged watersheds where such nonlinear effects can be expected.

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List of Tables

TABLE 1. Summary of rainfall events

Event characteristics	Minimum	Mean value	Maximum
Total Rainfall depth (mm)	53.9	159.8	571.8
Rainfall before flow peak (mm)	37.0	124.3	436.1
Duration (hours)	30.0	86.2	162.0
Duration to peak (hours)	7.0	17.7	39.0
Average intensity (mm/h)	0.67	2.08	6.35
Intensity before flow peak (mm/h)	2.31	7.64	12.84
Peak flow (m^3/s),	2.9	26.5	149.1

TABLE 2. Summary of regression models linking ReFH model parameters to event characteristics.

ReFH parameter	Event characteristics	R^2	Slope	p-value
C_{max} (mm)	$depth$ (total)	0.04	-0.29	0.341
C_{max} (mm)	C_{ini}	0.01	87.8	0.658
$ln[T_p]$ (hours)	$ln[depth]$	0.40	-1.08	0.000
T_p (hours)	C_{ini}	0.10	-3.16	0.081

TABLE 3. Ratio of Time-to-peak (Tp) and peak flow of design hydrographs ($qmax$) obtained using the non-linear Tp model and a fixed Tp estimate.

Return period	Design rainfall depth (mm) $D_c = 5$ hours	Ratio of Tp	Ratio of $qmax$
10	166	0.44	1.55
50	230	0.35	1.66
100	253	0.33	1.72
200	275	0.31	1.77
500	309	0.29	1.81
PMP	454	0.22	1.81

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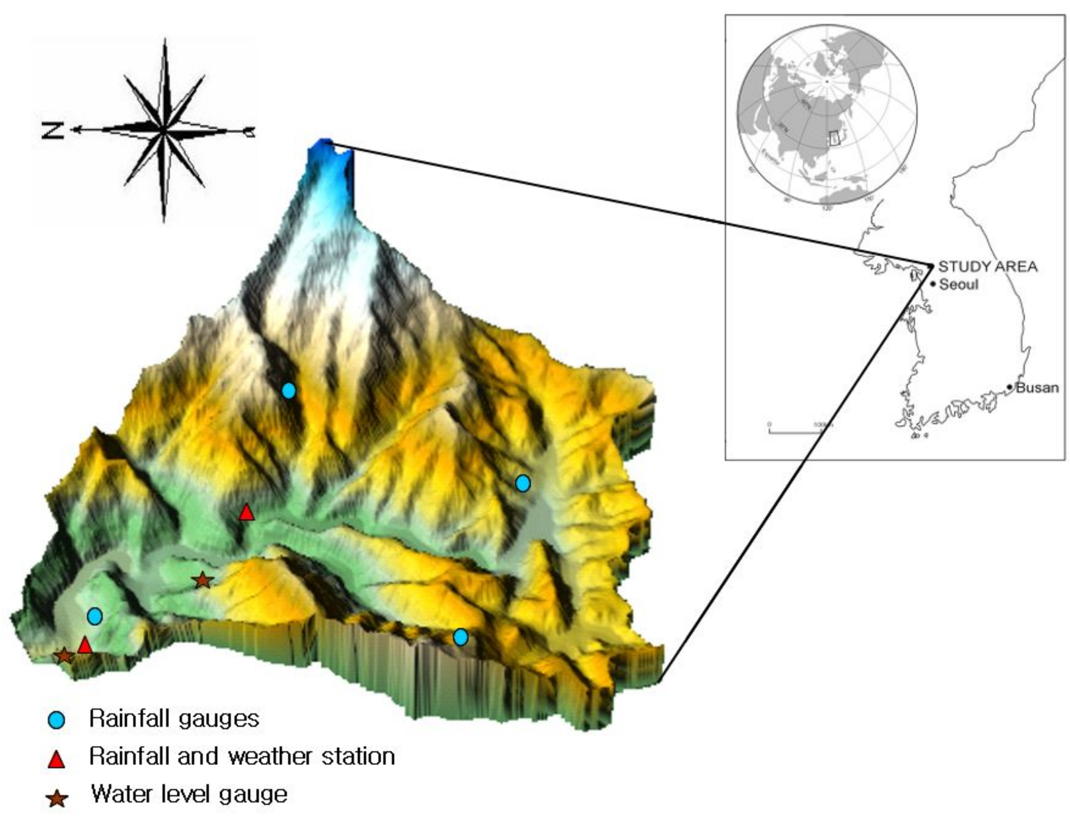
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Busan
Rainfall gauges
Rainfall and weather station
Water level gauge

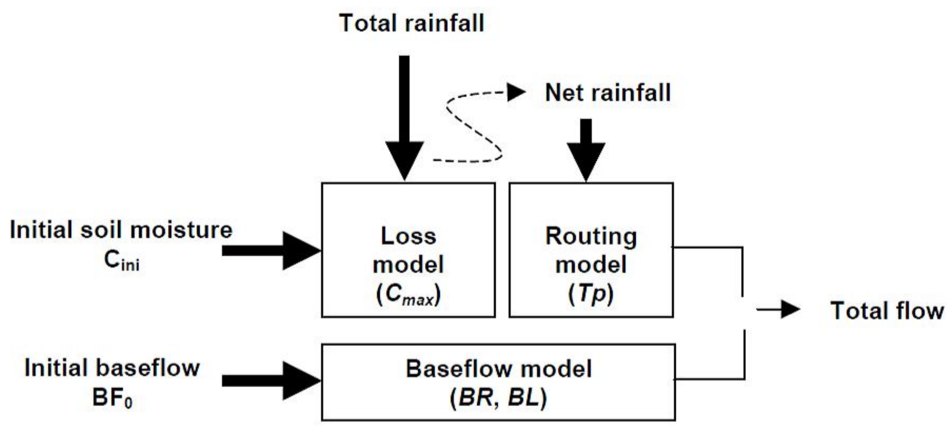

FIG. 2. Structure of ReFH model, including links between loss, routing and base-flow model [©NERC (Centre for Ecology & Hydrology)].

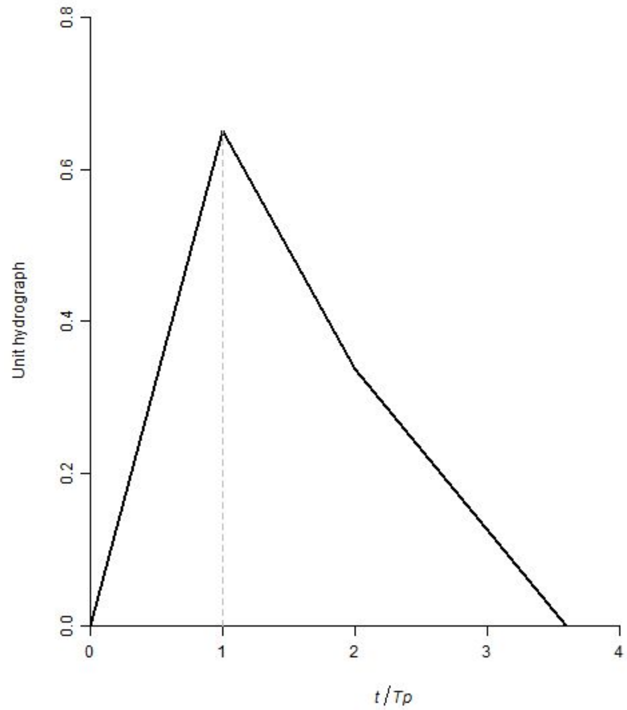

FIG. 3. ReFH kinked triangular IUH.

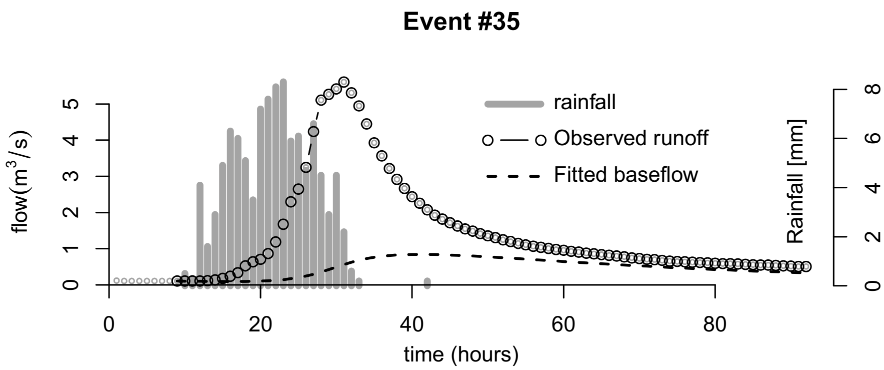

FIG. 4. The ReFH baseflow model fitted to an observed hydrograph. Broken line represent baseflow model. Darker colours represent selected event data.

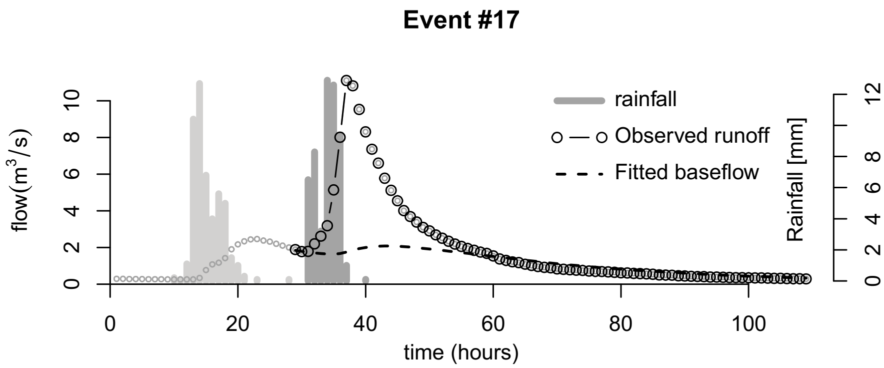

FIG. 5. The ReFH baseflow model fitted to an observed hydrograph with high initial baseflow. The broken represent the fitted baseflow model. Darker colours represent selected event data.

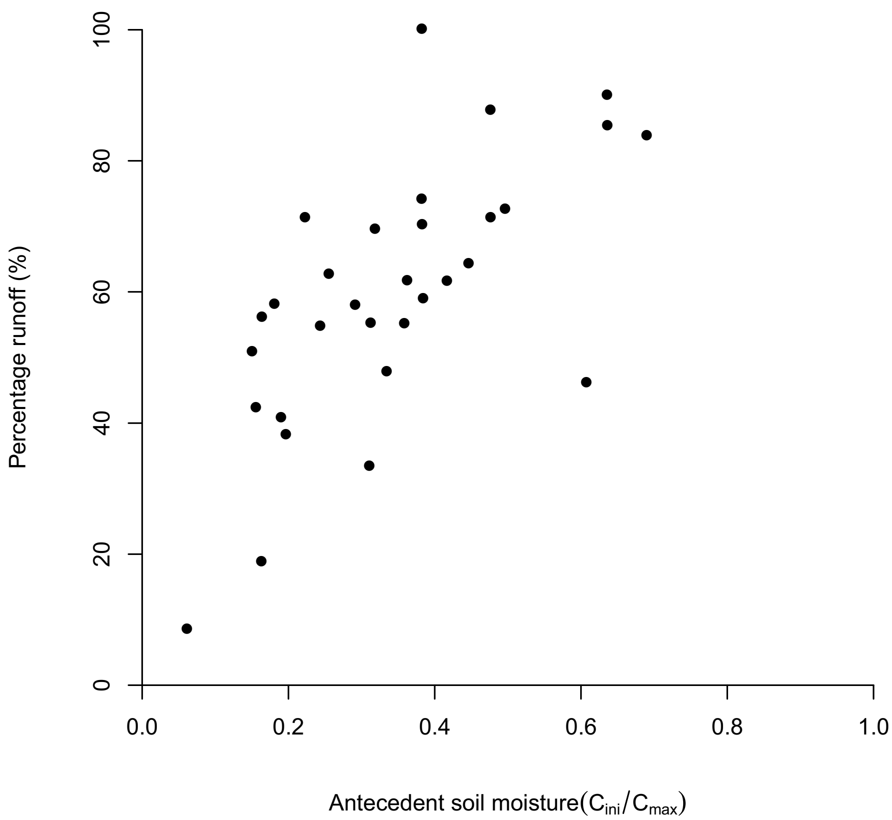

FIG. 6. Percentage runoff (%) for each of the 31 events plotted against antecedent wetness, expressed as the ratio between the soil moisture at the onset of each event and the total soil moisture capacity (C_{ini}/C_{max}).

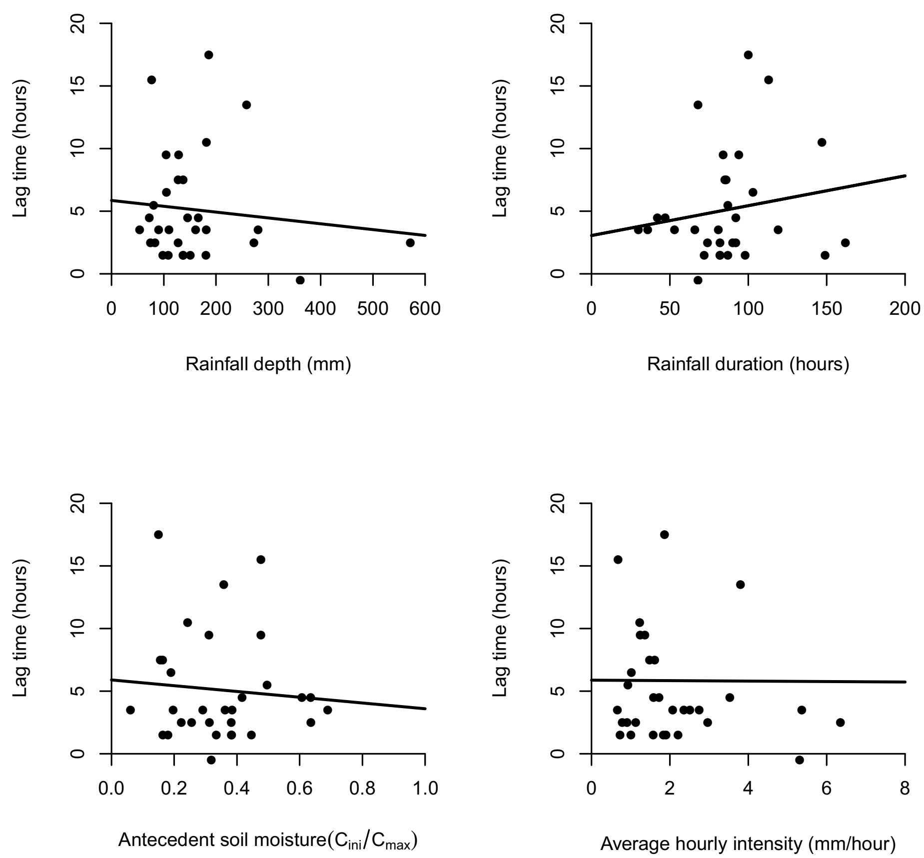

FIG. 7. Lag-time (hours) plotted against rainfall event characteristics.

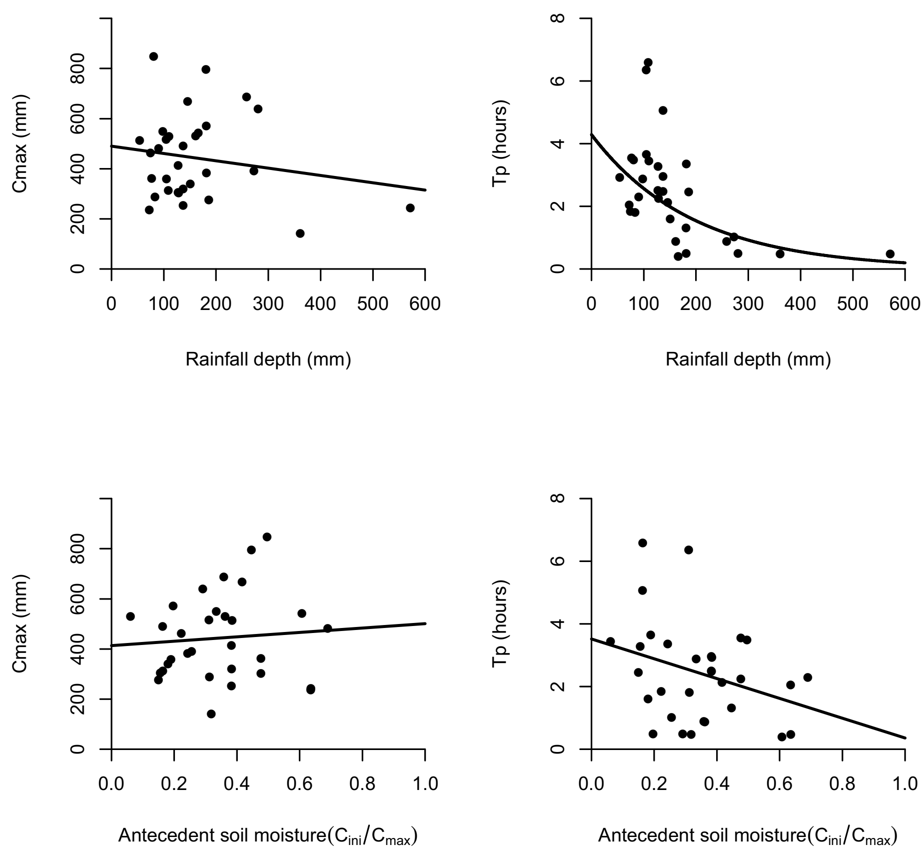

FIG. 8. ReFH model parameters C_{max} and Tp plotted against rainfall depth and antecedent soil moisture (C_{ini}/C_{max}).

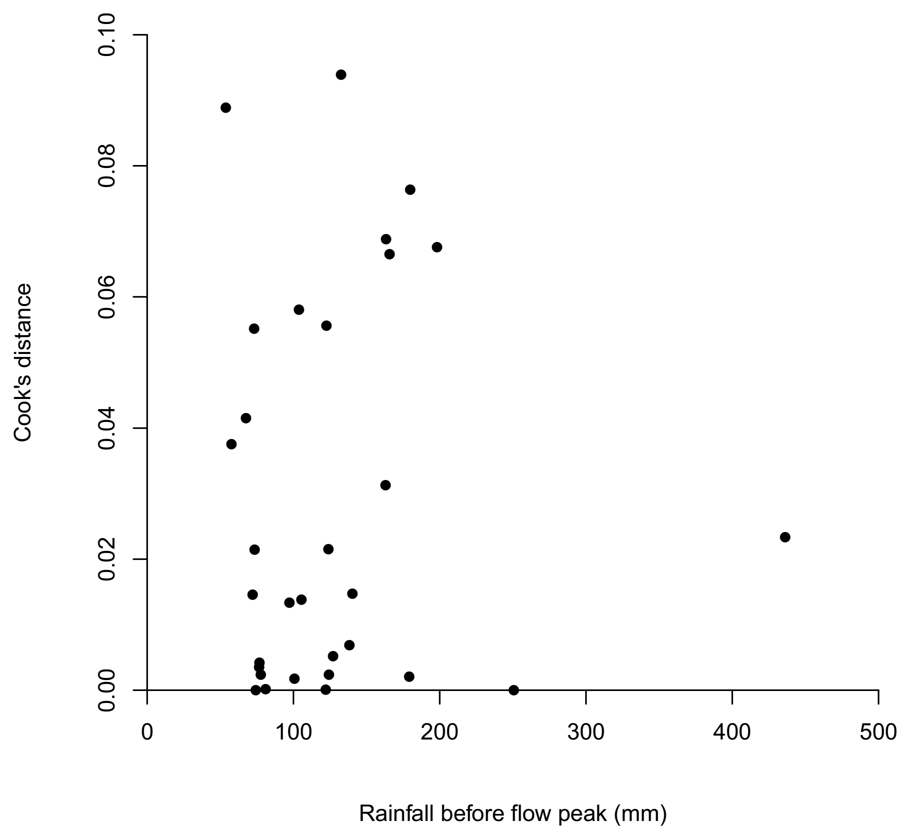

FIG. 9. Cook's distance plotted against rainfall depth between onset of event and flow peak.

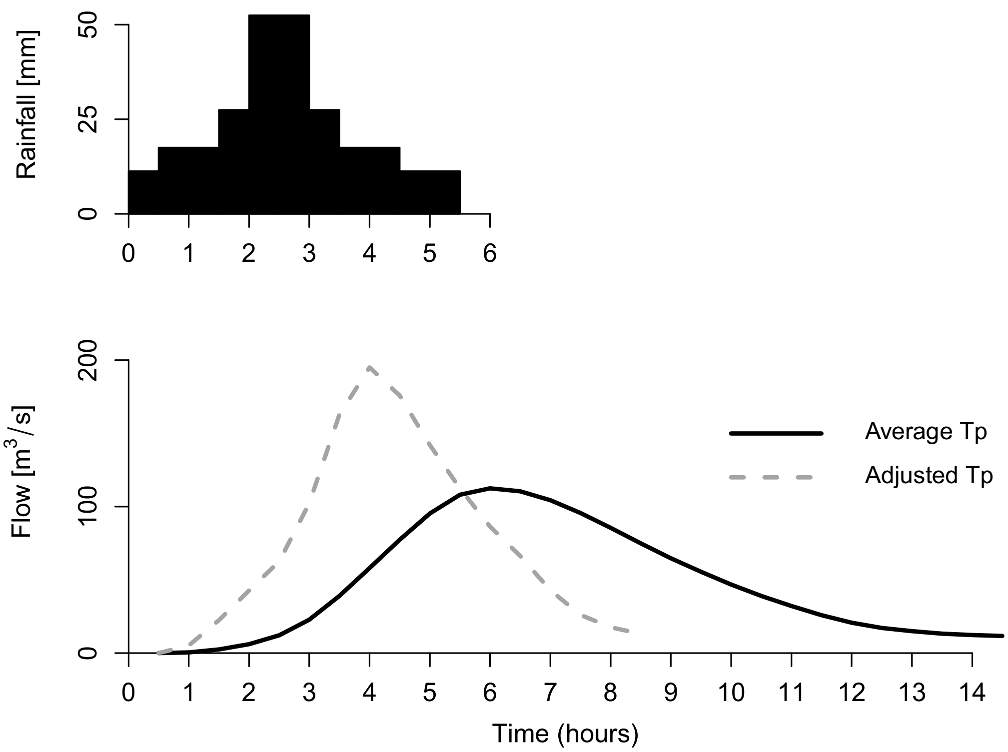

FIG. 10. Design flood hydrographs for a 100-year, $D_c = 5$ hour storm derived using ReFH with a Tp value estimated using (i) the average value across all events, and (ii) adjusted Tp according to Eq.(4).