The impact of rainfall variability and hydrological regimes on flood frequency

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Abstract: *The aim of this paper is to investigates the impact of within-storm rainfall variability and catchment response time and how these interactions are critical in determining flood frequency. Using deterministic rainfall-runoff model, hydrological regimes ranging from fast to slow are identified on the basis of the catchment response time. The model uses generated hourly rainfall time series adapted to climatic condition in Lampung province coupled with a hypothetical catchment using catchment properties suitable to this region. This study highlights the importance of within-storm rainfall pattern in determining flood peaks, particularly in fast regime. It shows that the difference of flood peaks in fast regime resulted from low to high within-storm variability may reach up to 223 %, while those in slow regime resulted from low to high within-storm variability may reach up to 107 %. The results of this study provide insights into the complex interactions between rainfall variability and hydrological regimes in the rainfall-runoff process, which are shown to have a significant impact on the resulting flood frequency curves.*

Keywords: *within-storm, rainfall variability, hydrological regime, flood frequency*

1. INTRODUCTION

Rainfall-runoff transformation is the complex interactions between climatic inputs such as rainfall intensity and evaporation and the landscape properties. For any storm event, the flood peak is a function of storm properties and the response time of the most dominant flood producing process. The dominant flood producing process is determined by temporal scales of rainfall and hydrological regime existent within the catchment. Rainfall intensity exhibits temporal variability at a multiplicity of timescales, consisting of storm, within-storm, between-storm, seasonal, inter-annual and inter-decadal variabilities. Similarly, the catchment rainfall-runoff response is associated with processes such as overland flow, subsurface flows and baseflow which also operate at range of time scales, arising from the multiplicity of pathways that water takes to the catchment outlet and associated travel distances and travel speeds.

The importance of within-storm pattern in the rainfall-runoff transformation in fast regime was first introduced by Robinson and Sivapalan (1997). Fast regime is defined as the regime where the average duration is approximately the same as the concentration time while the interval between storms is much longer than concentration time. In slow regimes, however, multiple storms and seasonality are more dominant. The time scales of subsurface flow and evapotranspiration, and longer time scales associated with rainfall, e.g., seasonality, are also important since together those variables determine the antecedent flow and soil moisture conditions in the catchment as it is established through the catchment's water balance (Jothityangkoon *et al.,* 2001).

The within-storm distribution of rainfall intensity is stochastically governed by an indicator of the variability, where the temporal patterns may be of small, medium or high variably. An investigation into the effect of different temporal patterns and the variability of within-storm rainfall intensity on flood was intensively discussed in Kusumastuti et al. (2007) and Kusumastuti (2009). The inclusion of within-storm rainfall intensity has a consequence that the time window in examining the hydrological process becomes more detail. Thus the timescale of hydrological model should be sufficiently small, e.g. in hourly time step.

The focus of this paper is on systematic analysis of timescales associated with rainfall variability and hydrological regimes and the effects of these on flood frequency behaviour. The aim of this study is to investigate the impact of rainfall variability, particularly within-storm temporal pattern, coupled with hydrological regimes and their impact on flood frequency.

2. METHODOLOGY

2.1. Rainfall Model

The rainfall model is adopted from the work Kusumastuti *et. al.* (2007, 2008a, 2008b) and Kusumastuti (2009) and it was modified to suit the rainfall characteristic in Lampung. Therefore the first thing to be done examining the rainfall data used in this study to define the average intensity, storm duration and interstorm period as well as the likely within storm pattern. Rainfall data used in this study is collected from Meteorological Bureau BMG Radin Inten, Lampung. Ten years of rainfall data from 2001 – 2010 is collected in hourly basis. Updated from previous study (Kusumastuti, 2009) the statistics of rainfall duration classes from the rainfall data is presented in Table 1.

Table 1. Statistics for Rainfall Duration Classes

Class	Duration Range	Events	$E[i\|t_r]$, mm/h	$CV^2[i\|t_r]$
1	$3 \le t_r < 6$	212	4.052	1.328
2	$6 \le t_r < 10$	84	2.198	1.231
3	$10 \le t_r < 17$	38	1.948	1.233
4	$17 \le t_r < 30$	10	1.707	1.086
5	$30 \le t_r < 100$	5	1.430	1.180

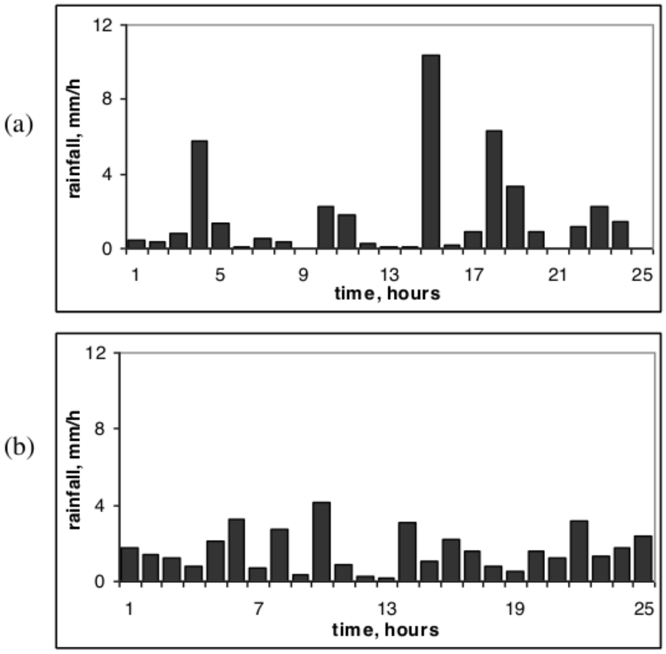

Figure 1. The variability of individual storms in the rainfall time series for (a) η =1 and (b) η =3

The rainfall model is capable in generating synthetic time series of rainfall consists of rainfall events where the occurrence, duration, average intensity and intensity pattern in a rainfall event is governed by probability density. The type of statistical distribution used to define rainfall properties and the equations used were explained in detail in previous works mentioned above. In this model, the mean storm intensity is further disaggregated to hourly intensity pattern. The variable which determines the within-storm pattern is called η. The magnitude of this parameter controls the patterns of rainfall variability within the event around the median. The higher the values of η, the more the values tend to be centered around the median. On the other hand, the smaller values of η, the more values are distributed at the extremes. Figure 1 illustrates typical rainfall hyetographs generated by the model for different values of η. The average intensity, and hence the total rainfall volume, is the same in both cases. The simulated patterns show that lower η values generate highly variable, while higher η values generate less variable rainfall, approaching nearly uniform rainfall intensities.

2.2. Rainfall Runoff Model

A conceptual nonlinear bucket model is used in this study. The bucket model is a conceptualisation of the hydrological process within a catchment, which transfers the rainfall input into runoff as a function of precipitation (i), storage (S) and evaporation (E_p). The flow components in the model include subsurface flow (Q_{ss}) and surface flow (Q_{se}). Potential evaporation (E_p) is also partitioned into bare soil evaporation (E_{bs}) and transpiration (E_{veg}). Basically the model assumes that a catchment works like a bucket with two thresholds; a field capacity and bucket capacity thresholds. A field capacity threshold determines that above the threshold subsurface runoff occurs and bucket capacity threshold determines that above the threshold surface runoff occurs. The equation used to describe the process within the catchment is the water balance equation :

$$\frac{dS}{dt} = i(t) - Q_{se}(t) - Q_{ss}(t) - E_{bs}(t) - E_{veg}(t) \qquad (1)$$

The field capacity threshold S_{fc} is a function of catchment-average field capacity, f_c, and the catchment-average soil depth, D. The bucket capacity, S_b, is assumed to be equal to $S_b = \square \phi D$, where ϕ is the catchment-average soil porosity. Based on the available soil depth data, the bucket capacity used for the majority of this study is 500 mm. Potential evaporation is obtained from measured pan evaporation data from Branti Meteorological Bureau, Lampung with an annual pan evaporation of approximately 1700 mm.

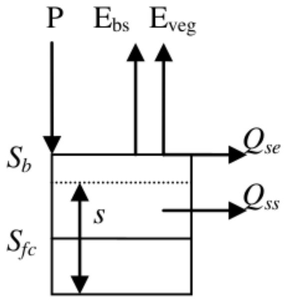

Figure 2. Bucket model configuration

The time concentrations used in the deterministic rainfall-runoff model vary from one hour to few days. This illustrates the time concentration from various places in Lampung Province, which can take hours to days. For simulation it is used t_c = 1 hour, 1day, 3 days and 7 days.

3. RESULTS AND DISCUSSION

In order to examine the role of interactions of rainfall and catchment timescales, this study used the water balance equation (Equation 1). In that equation rainfall intensity varies at variety of timescales. Correspondingly, the catchment response is related with different processes which operate at different timescales. Therefore the magnitudes of flood peaks are affected by the interactions between rainfall timescales and timescales of catchment response.

To examine the effect of the extent of within-storm temporal pattern upon flood frequency, rainfall time series with two different η values, i.e. $\eta = 1$ and 3 were taken into account. In addition to within-storm pattern, catchment response time with four different values, i.e. $t_c = 1$ hour, 1 days, 3 days and 7 days were considered. Figure 3 presents the impact of each η value in conjunction with catchment response time upon flood frequency. The graph shows that the variation of within-storm pattern significantly impacts the magnitude of flood peaks at small catchment response time (Figure 3a) and has lesser impact toward greater catchment response times.

Based on the hydrologic response of a catchment expressed in water balance, the impact of within-storm variability representing variability at small timescales, is most significant for a fast response mechanism such as surface runoff. Conversely, mechanisms with large timescales such as subsurface flow will attenuate the small timescale variability. Within-storm patterns have an observable impact upon the flood frequency curves as shown in Figure 3, where at the same return period the highest flood peaks were produced by the larger variability of within storm pattern or the lower η. Table 2 confirms that the difference of flood peaks resulted from those two within-storm temporal pattern is about 2.23 times and 1.47 times at return periods of 100 and 10 years respectively for $t_c = 1$ hour. For $t_c = 7$ days the difference of flood peaks resulted from those two within-storm temporal pattern is about 1.07 times and 1.02 times at return periods of 100 and 10 years respectively. Furthermore, Table 2 also presents the impact of catchment response time on flood frequency, where flood peaks, using high within storm variability, at return periods of 100 years for $t_c = 1$ hour is 2.38 times of that for $t_c = 7$ days. Using low within storm variability, flood peak at return periods of 100 years for $t_c = 1$ hour is 1.14 times of that for $t_c = 7$ days.

In the theory of hydrological regime in the subregion (Robinson and Sivapalan, 1997) with the small values of t_c the catchment responds so fast that the discharge hydrograph is the same as the rainfall hyetograph. In contrast, with high values of t_c the catchment responds so slowly that it does not differentiate between storm and interstorm periods. Discharge will be governed by the history of previous rainfall events and seasonal rainfall. This is called very slow regime. Those two regimes correspond to extreme regimes. Other regimes such as fast, slow and intermediate regimes will be governed to smaller extent by the effects of fine-scale structure (within-storm patterns) and long-timescale variation (previous rainfall history). The selection of catchment response time in this study represents fast to slow regimes. Catchment response time $t_c = 1$ hour can be defined as fast regime, this is identified by the significance of within-storm rainfall pattern in affecting the flood peaks (Figure 3a). Catchment response time $t_c = 1$ to 3 days can be considered as intermediate regimes where smaller extent of within-storm pattern and previous rainfall history have impact on flood peaks (Figure 3b and c). Catchment response time $t_c = 7$ days represents slow regime identified by much smaller degree of within-storm pattern and greater degree of previous rainfall history upon flood peaks.

Some of these implications of the various hydrological regimes correspond to flood peaks have been recognized in hydrology and widely used in flood estimation. For example, flood estimation in urban catchments relies heavily on the use of rainfall temporal patterns. Similarly, in the rational method of flood estimation for small urban and nonurban catchments, the duration of the design storm usually is considered the same as the catchment response time (Pilgrim, 1987). On the other hand, slow regimes are generally related to large river catchments. Catchment response from such catchment is sensitive to multiple storms. The result of this study highlights the importance of the use of within-storm pattern in fast regime. It is observed from other studies about catchment hydrology in Lampung province (Kusumastuti and Jokowinarno, 2009 and Suhendra, 2011) that some sub catchments, especially those located in urban catchments and heavily populated, have catchment response time in few hours or even less than an hour. Therefore it is important to consider within-storm rainfall pattern in the flood estimation.

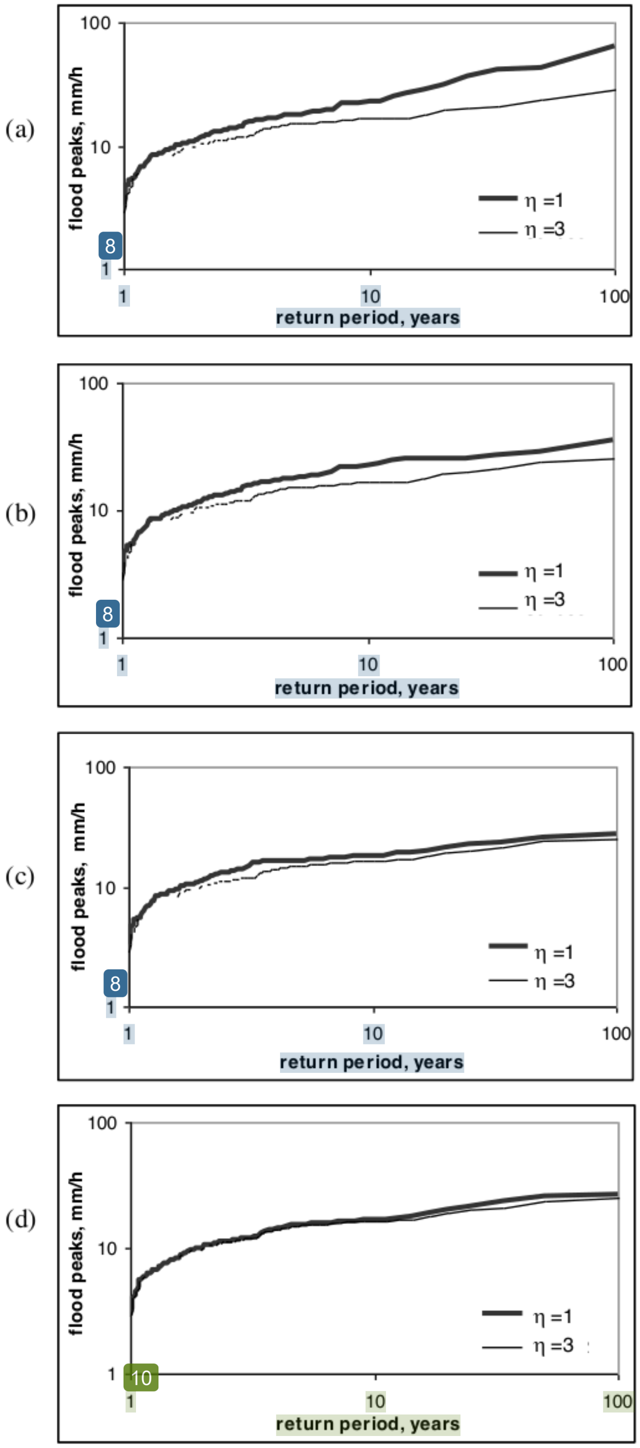

Figure 3. Flood frequency curves generated by rainfall-runoff model using η=1.0; and 3.0 for (a) t_c = 1 hour, (b) t_c = 1 day, (c) t_c = 3 days and (d) t_c = 7 days.

Table 2. Flood peaks related to catchment response time and within-storm pattern

Flood Peaks (mm/h)				
Catchment response time	At return period of 100 years		At return period of 10 years	
	$\eta = 1$	$\eta = 3$	$\eta = 1$	$\eta = 3$
t_c = 1 hour	64.34	28.85	24.76	16.83
t_c = 1 day	36.00	25.52	22.85	16.57
t_c = 3 days	28.74	25.29	18,10	16.42
t_c = 7 days	26.98	25.14	16.80	16.38

4. CONCLUSION

This paper has addressed the question with respect to flood frequency, i.e. what is the impact of rainfall variability, particularly within-storm temporal pattern, and hydrological regimes on flood frequency. Within-storm rainfall pattern is significant in fast hydrological regime as surface runoff generation mostly generated at small catchment response time. In slow hydrological regime within-storm pattern has very less impact compared to multiple storms occurred previously which are more dominant in affecting the flood peaks.

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