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Investigating the Role of Rainfall Variability on the Hydrological Response of Small Tropical Upland Watershed

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Abstrak

Excessive soil losses found in many upper basins in Java which causing severe problem in the lowland areas due to extreme hydrological response. The objective of this research is to study the role of rainfall variability (spatial variability, intensity and duration) on the hydrological response of small tropical upland watershed. To run and test this scenario, a watershed with a good weather dataset and experience soil loss problem was selected. Therefore, Bompon Watershed were selected to perform the model. In order to investigate the hydrological response of different rainfall variability, LISEM was sed. Three scenarios of comparison were designed: different rainfall interpolation, different direction of rainfall movement, high intensity-short duration and low intensity-long duration rain. Initial moisture content (thetai) was found as the most sensitive variable for all indicators when all input variables value increased. When the input variables values decreased, thetai was found as the most sensitive variable for changing in total discharge, whereas saturated hydraulic conductivity (Ksat) was the most sensitive variable for changing in peak of discharge.

INTRODUCTION

Located in the tropical region, Indonesia experiences huge amount of rainfall which would potentially contributes to disaster. An accurate prediction of runoff during a heavy rainfall event is an important part of disaster management (Christanto 2008). For example, floods are one of the most devastating hazards induced by extreme rainfall (Penna, Borga, and Zoccatelli 2013; Wicaksono and Hidayat 2016; Young, Liu, and Wu 2017). Flood create significant damages to economy and numerous losses of life (Azmeri, Hadihardaja, and Vadiya 2016; Bishop et al. 2012; National Research Council (U.S.). Committee on Assessing the Costs of Natural Disasters. 1999; Svetlana, Radovan, and Ján 2015). A lot of efforts have been made to develop better understanding of characteristics, processes, and responses in a watershed. This better understanding will lead to more practical step such as flood warning and drought alert (Anwar et al. 2018; Christanto et al. 2018; Cools, Innocenti, and O'Brien 2016; Koriche and Rientjes 2016; Yu, Nakakita, and Jung 2016).

Complicated and nonlinear rainfall-runoff process in tropical catchment have been studied by various methods. Generally rainfall and runoff in tropical catchment are spatially and temporally varies due to the influences of weather conditions, terrain, land-use, and soil types (Gebremicael et al. 2013; Lin et al. 2015; Shi et al. 2013). Direct mapping of the hydrologic variables and extract their relationship from field measurement considered to be the best method that will lead to better understanding of the characteristics, processes, and responses

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in a tropical watershed. During a rain event, water is initially absorbed by soil and infiltrates into the soil base on their soil porosity, initial soil moisture and soil depth (Kværnø, Stolte 2012; Sheikh et al. 2010). The remaining water that does not infiltrated into the soil will flows as surface runoff (Bates, Aryal 2014; Cabral et al. 1992; Sujono 1995). The runoff will become a problem when the volume and the velocity of water increases. Based on the water cycle process, runoff may increase linearly with precipitation. Many studies found a strong relation between precipitation and runoff in the humid tropical watershed (Kinosita.1983). On the other hand, dissimilar responses of runoff were found in the different rainfall events occurrences. Different duration and intensity of rainfall may result different runoff (Bennett et al. 2016; Emmanuel et al. 2015; Sadeghi et al. 2016; Zhang et al. 2015).

The objective of this paper is to develop a new understanding the effects of spatial variability of rainfall and different intensity and duration of rainfall events to runoff generation in tropical humid watershed. Sensitivity analysis will be carried out to assess the prediction performance. In order to design mitigation strategies, runoff assessment studies are expected to come up with result of runoff characteristics. For this reason, event based model is used in this study due to its easiness to calibrate and does not need a long hydro-meteorological records. The Limburg Soil Erosion Model (LISEM) is a physical event based model which possible to calculate runoff and the effect rainfall variability (De Roo et al. 1996a). It has widely been applied in many studies (Baartman et al. 2012; Boer & Puigdefábregas 2005; De Roo, Jetten 1999; Hessel et al. 2007) also in the tropical area with adequate calibration (Gomes et al. 2008).

RESEARCH METHODS

The process of this research is described in the following flowchart. The flow of this research was set to respectively correspond to the objectives. The general sequential step was started by the analysis of daily rainfall data to explain the spatial variability. This analysis was then used in performing interpolation of detail rainfall event to be use in the simulation of runoff and erosion.

The research activities will be conducted at Bompon Watershed, part of Bogowonto Catchment, Java Island, Indonesia (figure 1). This catchment is located between 7°32’25” – 7° 34’9” S and 110° 4’39” – 110° 4’24” E. The topography of the catchment is generally rugged and mountainous and ranges from msl on the nort part of the basin and msl in the south part of the basin. It covers 300 ha catchment area.

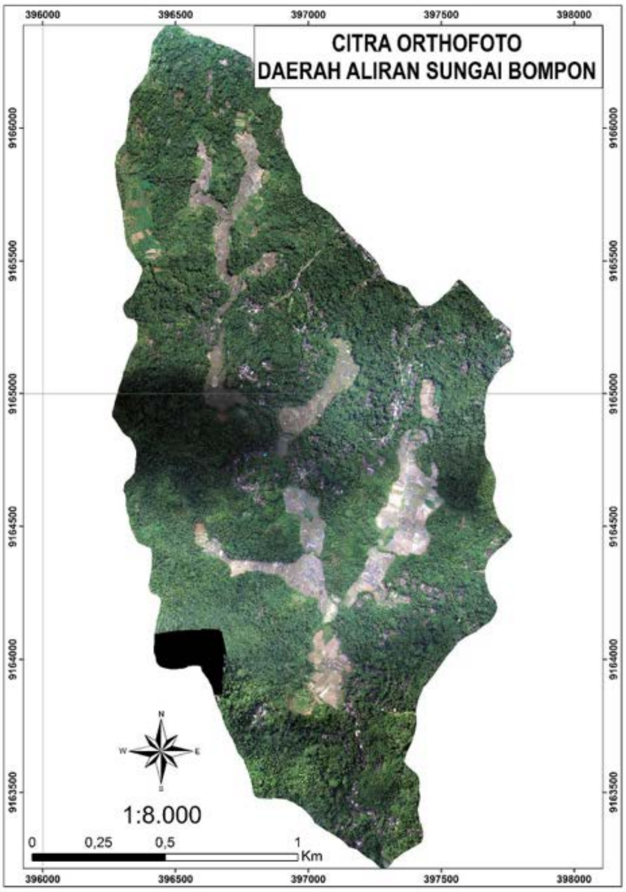

Figure 1. Study area

Limburg soil erosion model (LISEM) was selected to be used due to its ability to spatially simulate runoff and erosion per event of rainfall. In other words, different variation of rainfall event should be able to be simulated by this event based LISEM model and this simulation would almost certainly resulted in different responds of runoff and soil erosion. In order to simulate the physical processes in discharge generation, a large number of data are needed as the input of the model. Jetten (2002) explained the input of LISEM model can be generated from four main maps: channel map, digital elevation model (DEM) map, land cover unit map, and soil texture unit map.

Several scenarios were designed to simulate different spatial variation of rainfall event. They are: 1. Rainfall from top to down of the watershed,

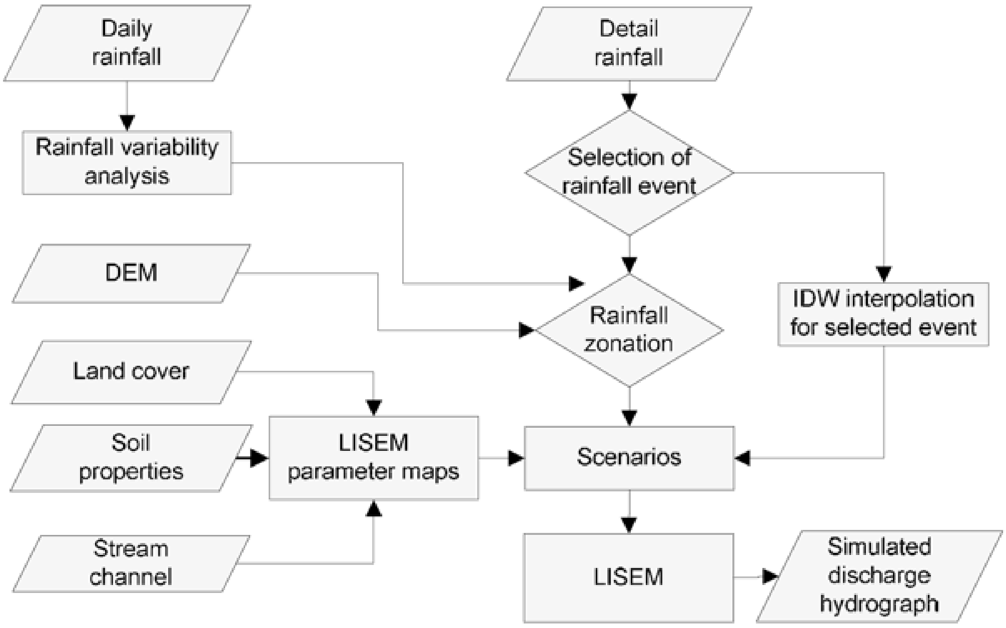

Figure 2. Research Flow Chart

and 2. Rainfall from down to top of the watershed 3. Model run with IDW 4. Model run with rainfall zonantion. These results different discharge hydrographs output to be analyzed. The flowchart of this research is described in figure 2.

Rainfall event for runoff modelling

By means of LISEM as an event-based model, rainfall data analysis aims to select a rainfall event which give more response to the hydrological process (Baartman et al. 2012). The selection of rainfall event is based on the relation between data from the rainfall event with the discharge data. The reason for this is because a high intensity of rainfall does not always followed by a large amount of discharge, it is also depends on the soil moisture condition (Hessel et al. 2003a; Morgan 1995). In the same way initial moisture condition of the soil was also taken into account in selecting the event. In this way, Baartman et al. (2012) limited a <60 minutes interval of no rain to consider two separated rain as one event.

With respect to the previous study mentioned above, we used the category of > 25.4 mm/event and considered that a rainfall event to have ended if no rainfall occurred in more than 60 minutes. In order to answer research questions, rainfall event scenarios are needed to be built. Scenarios were designed based on the three following categories:

1. Two events with different type of interpolation (Inverse Distance Weighting (IDW) and rainfall zonation).
2. Two events with different direction of storm movement. One is when storm moves from higher elevation to lower elevation area, and the other one is when storm moves from the lower to the highest elevation area.
3. Two events with high intensity-short duration rain and low intensity-long duration rain. The selection of these two events is based on the event index equation (EVI) proposed by Baartman et al. (2012).

Rainfall Scenario

This scenario was constructed based on the event index equation introduced by Baartman et al. (2012). It describes the relationship between on maximum intensity (Pmax; mm/h), total precipitation (Ptot; mm), and total duration (T; min) in the equation (1):

$$Evi = \frac{Pmax * Ptot}{T} \quad \text{Eq. (1)}$$

where high EVI represents intense rain storm of short duration and high peak intensity, and low EVI describes rainfall with low intensities but long duration. In this way, the watershed experienced a uniform (not vary) rain. Two events with different EVI were selected, and these two selected events must have had different rainfall characteristics (intensity, total rain, and duration). In order to be able to be compared, these two events should have had the same total rain (Ptot) first, because factors which are considered in the EVI equation are only the maximum intensity (Pmax) and duration (T).

For an illustration, two rainfall events with different EVI are selected: event 1 and event 2. The total rain of the event 2 (Ptot 2) must then be normalised to have the same total rain value as event 1 (Ptot 1). As a consequence of changing in total rain in event 2 (Ptot 2), the intensity of the event 2 (Pmax 2) should also be adjusted to a new value. After the total rain (Ptot 2) has been normalised and the intensity (Pmax 2) hasbeen adjusted, then the two rainfall event ready be compared with respect to the intensity and duration characteristics relationship defined in the EVI's equation.

This normalization and adjustment process will also affects the EVI. Therefore, the new EVI value of the second event (event 2) must then be checked if it still in the contrary condition compare to the EVI value of the first event (event 1). For instance, if before the normalization and adjustment, event 1 has an EVI value higher than event 2, then it should still be as it was after the normalization and adjustment. The illustration of normalization and adjustment process is described in the following steps.

In order to normalize Ptot 2 to be equal to Ptot 1, the ratio (x) of Ptot 1 to Ptot 2 is calculated as proposed by Baartman et al. (2012):

$$\frac{Ptot1}{Ptot2} = x \leftrightarrow Ptot1 = x * Ptot2 \text{ (equation 2)}$$

where Ptot 1 = total rainfall of even 1, Ptot 2 = total rainfall of event 2, and x = the ratio of both total rain.It is known that total rain (Ptot) is a function of total sum of each time step of rain in the event period(P1+P2+P3+…). That relation is described in equation 3:

$$Ptot = f(P) = \sum_{i=1}^{n} P \text{ (equation 3)}$$

$$Ptot = P1 + P2 + P3 + \cdots + Pn \text{ (equation 4)}$$

By considering equation 1 and 3, equation 2 is then becoming as follows:

$$f_1(P) = x * f_2(P) \text{ (equation 5)}$$

Therefore, the precipitation on each rainfall time step of the adjusted event 2 can be calculated with equation 7 below:

$$f_1(P) = f_1 * (P_1 + P_2 + P_3 + \cdots + P_n)$$
(equation 7)

Another way to calculate the Pmax of new adjusted event 2 is by the substituting the Ptot 1 to EVI equation of Ptot 2. The process is described as follows:

$$EVI_1 = \frac{Pmax_1 * Ptot_1}{T_1};$$

$$EVI_2 = \frac{Pmax_2 * Ptot_2}{T_2} \text{ (equation 8)}$$

if *Ptot1=Ptot2*, the next equation is as follow:

$$Pmax_2 = \frac{Pmax_1 * Evi_2 * T_2}{Evi_1 * T_1} \text{ (equation 9)}$$

where number 1 and number 2 refer to the event's name.

Event-based Runoff Modelling

An event-based model was chosen to be used in this study to achieve the research objectives about variability of event based rainfall. LISEM has an ability to model and event based rainfall event. Software Open LISEM version 1.53 was used in the modelling process. Default settings of open LISEM version 1.53 which were applied in running the model are described in the following table:

Table 1.Open LISEM default input parameter settings

Input variable options	Model/value
Interception:	
-Stem flow fraction	0.050
-Canopy opens factor k	0.450
-Canopystorage-equation: crops	S=0.935+0.498*LAI-0.00575*LAI^2
Infiltration	Green and Ampt (1stlayer)
Kinetic energy	KE=a*(1-b*exp(c*I)) a=8.950; b= 0.520; c=0.042

In terms of resolution, the model was set to run with 5 m spatial resolution of input and output maps and 10 minutes of running step adjusted to the input data. The hydrograph, and sediment output of Open LISEM is in text file format. Dataset to run Open LISEM were constructed from 4 maps (channel map, digital elevation model, land cover unit map, and soil texture unit map) and 2 tables (table of parameter related to land cover unit, and table of parameter related to soil texture unit). When running Open LISEM with rainfall zonation, additional data needed are rainfall map (id.map) and rainfall data in text file format. A PC Raster script was used to extract database for running with Open LISEM.

RESULT AND DISCUSSION

Runoff modelling with two rain falls with different spatial variability

This first scenario is designed to compare the output runoff the model with two different rainfall interpolation maps input. The summary of the simulation result for these scenarios is given in table 2.

Table 2. Simulation summaries of two type of rainfall interpolation maps

Variables	with rainfall zonation	With IDW
Total rainfall (mm):	32.3	32.8
Total discharge (mm):	1.9	0.4
Percentage of total discharge/total rainfall (%)	5.75	1.21
Percentage of total infiltration/total rainfall (%)	88.72	93.10

All output variables of the model result simulated with rainfall zonation indicate higher value compare to result simulated with IDW. The magnitude (total and intensity) of the event and spatial pattern of the input rainfall map contributed these results. By looking at the larger amount of discharge resulted by simulation with zonation of rainfall compare to simulation with IDW, a Hortonian overland flow is likely to have occurred in the lower area which cause larger output of runoff.

Hydrographs of the simulations in figure shows that the peak time of water discharge is almost the same time for both simulations. Less amount of runoff from less magnitude of rainfall event subtracted with higher infiltration capacity of soil surface makes the overland flow (if any) flowing with less flow detachment capacity. This was because the runoff water infiltrated before reaching the channel. Since the paddy field are mostly located adjacent to the stream channel, rainfall with zonation which used to be higher in paddy field area (due to its uniformity along the zone) generated overland flow to transport sediment from paddy field directly to the channel.

Runoff modelling with two different direction of rainfall movement

Discharge resulted more by down to top (down-top) rain movement simulation compare to top to down (top-down) simulation although the top-down simulation experienced more amount of rainfall. This is because most of the rainfall in the top-down simulation infiltrated into the soil more than the down-top one.

From the simulation in table 3, it shows that simulation with down-top rain simulation resulted more discharge compare to top-down rain simulation. During the event, higher magnitude (total and intensity) of rainfall was recorded at station located in the lower elevation. The possible indication for faster response of discharge hydrograph of down-top simulation was because a part of rainfall falling downstream (near to the outlet) turned into discharge faster since it is easier for water to reach the outlet. However, the amount of water that turn into discharge might mainly came from the area around the channel because the down-top simulation shows that most of the runoff infiltrated into the soil before reaching the channel.

Table 3. Simulation summaries of two different rainfall directions

Variables	Down-top	Top-down
Total rainfall(mm):	19.1	25.3
Total discharge(mm):	0.17	0.07
Percentage of total discharge/total rainfall (%)	0.89	0.27
Percentage of total infiltration/total rainfall (%)	91.92	93.79

Sensitivity analysis

Sensitivity of the model was tested by increasing and decreasing for 20% the values of some input variables. It was found that the initial moisture content (*Thetai*), is the most sensitive variable related to 20% increasing of input value for all indicators assessed (134.87% increasing of total discharge, 163.35% increasing of peak of discharge, and 42.82% increasing of total soil losses), followed respectively by the saturated hydraulic conductivity (Ksat), the saturated volumetric moisture content (Thetas), and average suction at the wetting front (psi). For 20% decreasing of input value, the highest percentage change of total discharge is almost equal with the 20 % decreasing of Ksat and *Thetai* (49.17% and -50.13% of change in total peak discharge). It was found that 20 % decreasing of Ksat made 59.36% change to peak of discharge, whereas 20% decreasing of Thetai contributed to -54.86% of change in peak of discharge. In total soil loss, thetai was found as the most sensitive input variable 20% of change in Thetai resulted -33.64% of changing in total soil loss. Graphical visualization of the sensitivity analysis is given in Table 4, whereas the detail calculation result is described in Table 4.

Table 4. Estimated Regression Function Heteroscedasticity Model

Total discharge				Peak of discharge			
20% decrease		20% increase		20% decrease		20% increase	
variable	% change	variable	% change	variable	% change	variable	% change
ksat	49.17	thetai	134.87	ksat	59.36	thetai	163.35
thetas	33.29	Coh	2.40	thetas	41.35	Coh	2.72
Psi	32.31	Agg	0	Psi	40.01	Agg	0
N	2.50	N	-2.38	N	4.43	rr	-4.12
Nchan	2.50	Nchan	-2.38	Nchan	4.43	N	-4.19
rr	2.40	rr	-3.47	Rr	2.72	Nchan	-4.19
Coh	0	Psi	-23.78	Coh	0	Psi	-27.56
Agg	0	thetas	-24.27	agg	0	thetas	-28.17
thetai	-50.13	ksat	-31.96	thetai	-54.86	ksat	-34.96

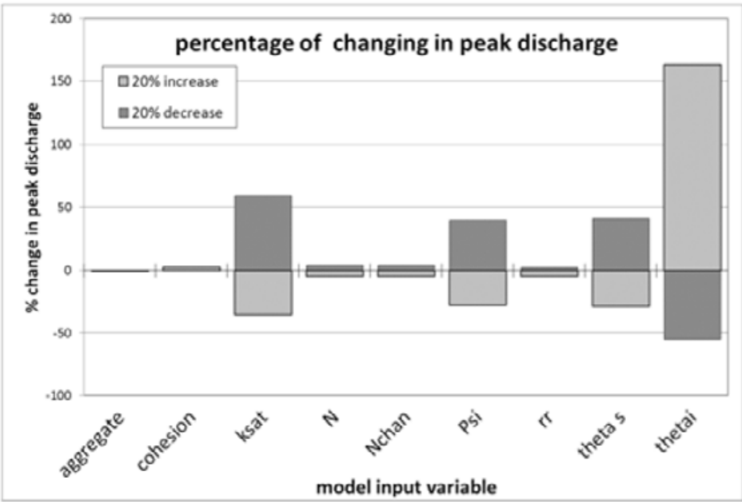

Figure 2. Percentage of Changing in Peak discharge

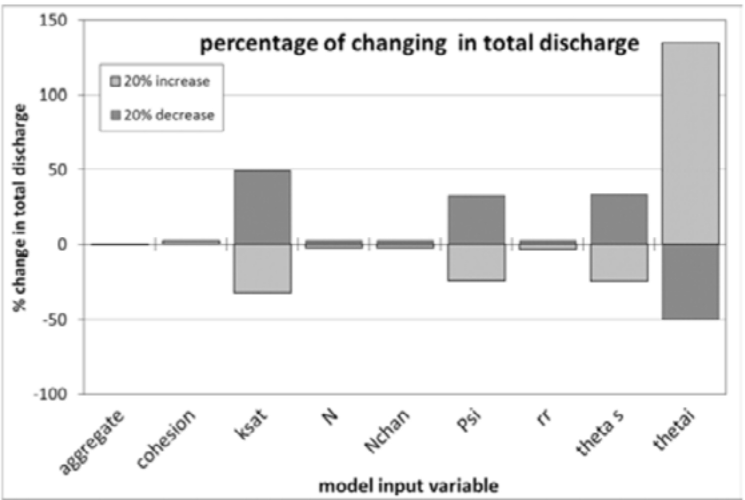

Figure 3. Percentage of Changing in total Discharge

CONCLUSION

Rainfall in the watershed is not uniform. Correlation coefficient (r) of precipitation is 0.7654 between Kalisari and Kwadearan (the highest and lowest station) and 0.9304 between the two closest station (Kwaderan and Bompon). The higher amount of runoff was found ~~more~~ when simulated with rainfall zonation compared with inverse distance weigh (IDW) interpolation. The earlier hydrograph of runoff response was founded when simulated with rainfall event moving from lower to higher elevation area (peak time at minute) compared ~~to~~ with rain moving from higher to lower elevation area (peak time at minute). The down to top simulation produced more water discharge than the down to top simulation. Discharge to rainfall delivery ratio is 0.89% for down to top simulation, whereas the top to down simulated 0.27% discharge to rainfall ratio. The high intensity long duration rain simulated more discharge (804638,9 m^3 with 7.01% discharge to rainfall ratio) than the short intensity-long duration rain (300008,3 m^3 with 2.61% discharge to rainfall ratio). When the input variables of the model were increased to 20% higher, initial moisture content (thetai) was found as the most sensitive variable to total discharge (134.87% increasing) and peak value of discharge (163.35% increasing). When the input variable were decrease to 20% lower, thetai become the most sensitive variable causing change in total discharge (decrease-50.13%) followed by saturated hydraulic conductivity Ksat (total discharge increase for 49.17%). In peak of discharge, Ksat is the most sensitive variable which caused 59.36% of increasing in peak of discharge. The model is also capable to simulate the land-use scenario and land management. Therefore, future work on land-use and land management scenario is recommended.

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