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Simple Method for Assessing Spread of Flood Prone Areas under Historical and Future Rainfall in the Upper Citarum Watershed

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Abstract

From 1931 to 2010 the flood frequency in Upper Citarum Watershed had increased sharply indicating the decline of the wateshed quality. With the change of climate, risk of the flood may get worse. This study aims to determine effective rainfall that caused flooding and to evaluate the impact of future rainfall changes on the flood prone areas. Effective rainfall which contributes to direct runoff (DRO) and leads to flooding was determined using regression equation relating the DRO and cumulative rainfall of a number of consecutive days. Mapping the flood prone areas was developed using the GIS techniques. Results showed that the effective rainfall which caused flooding was the rainfall accumulation for four consecutive days before occurrence of peak of DRO. The percentage of accuracy between estimated and actual flood maps was about 76.9%. According to historical rainfall, the flood prone areas spreaded at right and left directions of the Upstream Citarum River. If this area experiences the climate change, the frequency and flood extents will increase. This study can only identify locations and possibility of flood occurence but it cannot demonstrate widespread of flood inundation precisely. However, this simple approach can evaluate the flood frequency and intensity quite well.

Keywords: effective rainfall; direct runoff; flood prone area; climate change

1. Introduction

Citarum Watershed is one of the important watersheds in West Java that experienced degradation (Fares and Yudianto, 2004; D'Arrigo *et al.,* 2011; Boer *et al.,* 2012). This condition contributes to the increase of flood and drought severity in the watershed. One of the flood prone areas in the Upper Citarum Watershed is Cekungan Bandung, a plateau area surrounded by mountain range forming a basin (Bronto *et al.,* 2006). Such topographical condition causes the rainfall-runoff on the mountain range tend to flow into the basin area, resulted in flood disaster at right and left side of the Upper Citarum River. According to BBWS Citarum (2010) and Kartiwa *et al.,* (2013), the flood frequency in the study area is increasing from year to year as, the Upper Citarum Watershed is continuing to degrading. At present the condition of the the Upper Citarum Watershed is very critical (Apip *et al.,* 2010).

Flooding will occur when the watershed system receives unusual high rainfall intensity or the prolonged rainfall event so that the streamflow rate exceeds the channel capacity (Dingman, 1994). In general, the volume of flood equals the volume of direct runoff, caused by effective rainfall falling onto that watershed (Viessman *et al.,* 1977; Sraj *et al.,* 2010). Based on the information of the effective rainfall, the time period and rainfall threshold that resulted flooding can be estimated. Montesarchio *et al.* (2009) used value of rainfall thresholds for flood warning where the thresholds are estimated using the hydrological modelling to determine a critical discharge that exceed a particular cross section.

The effective rainfall and direct runoff in a watershed system can be presented in simple empirical model, i.e. a linier model (Dingman, 1994; McIntyre *et al.,* 2007; Abustan *et al.,* 2008; Ruminta, 2009). Based on this model, the occurrence of flooding can be rapidly determined although this model cannot identify the flood location precisely. This means that both information of historical flood events and GIS techniques are needed to identify flood location or to map flood prone areas. Knebl *et al.* (2005), Schmocker-Fackel *et al.* (2007), Zheng *et al.* (2008), Sarhadi *et al.* (2012) have developed a hydrology modeling using GIS tools to identify runoff process and map a spread of flood inundation or the flood prone areas.

Based on the field problems and the previous research, this paper will focus on: (1) determining the duration of effective rainfall which caused flooding in the Upper Citarum watershed, and (2) predicting the frequency of flood events and spread of flood prone areas according to the current and future condition.

2. Materials and Methods

Research materials can be grouped into two: attribute data and spatial. The attribute data consist of the river discharge, historical and future rainfall, and the information of flood events. Historical rainfall constituted the yield of research from Dasanto et al. (2013, forthcoming) while the future rainfall was generated from climate model of RegCM3 with 20 km horizontal resolution run under SRESA1B scenario, and these data were acquired from CCROM-SEAP database. The flood information was obtained from the BBWS Citarum while spatial data covered a topographic map and image of Landsat-7 wer obtained from agency of Bakosurtanal and USGS, respectively.

2.1. Identifying the direct runoff

In a watershed system, magnitude and flood extents can be approached from value of DRO, defined based on the following equation:

$$DRO_i = Qf_i - BF \quad (1)$$

where DRO_i is the direct runoff which causes flooding; Qf_i is the runoff total measured at outlet of watershed, *BF* is the baseflow, and notation of *i* shows flood events. In this case, value of baseflow is estimated using the flow duration curve with the probability value of 90%.

2.2. Identifying effective rainfall

Rainfall which contributes on DRO and leads to flooding in the research area is referred to as effective rainfall. This data can be identified from yield of relation between the averaged areal rainfall and the DRO volume calculated for the watershed. Next, the following stages required to be performed:

1. Identifying rainfall total R(t) at the day of peak of direct runoff (DROp), and rainfall magnitude for six rain days before DROp and this is called R(t-1), R(t-2), ..., R(t-6).

2. Calculating the rainfall accumulation according to 7 scenarios (i.e. $R_0 – R_6$):
   - o R_0 = R(t)
   - o R_1 = R(t) + R(t-1)
   - o R_2 = R(t) + R(t-1) + R(t-2)
   - o R_3 = R(t) + R(t-1) + R(t-2) + R(t-3)
   - o R_4 = R(t) + R(t-1) + R(t-2) + R(t-3) + R(t-4)
   - o R_5 = R(t) + R(t-1) + R(t-2) + R(t-3) + R(t-4) + R(t-5)
   - o R_6 = R(t) + R(t-1) + R(t-2) + R(t-3) + R(t-4) + R(t-5) + R(t-6)

3. Building relation between DRO (result of Equation 1) and the rainfall accumulation scenarios (result of second step) for each flood event using regression model. Generally, this model can be defined as:

$$DRO_i = b_o + b_1 R_{hi} \quad (2)$$

where DRO_i is direct runoff for flood events ***i***, b_o and b_1 are constants of linier regression; R_{hi} is the rainfall accumulation for scenario-***h*** (***h*** = 0, 1, 2, ..., 6) and flood events ***i***, and ***i*** is the flood event which coincides with flood information as the date and flood location. Based on the best regression model (the highest R^2), the duration of effective rainfall which causes occurrence of direct runoff or flooding can be identified.

2.3. Frequency of effective rainfall

The effective rainfall probability can be estimated using the approach of the probability distribution model. There are two steps that need to be done in defining the probability distribution model, i.e.:

1. converting the daily rainfall (historical and future rainfall) into the rainfall data that match with duration of effective rainfall. In this illustration, the duration of effective rainfall is equal to the rainfall accumulation for four consecutive days before flooding and this is called R_4 (see Table 1)

Where ***R*** is the historical or future rainfall; $\boldsymbol{R_4}$ is the rainfall accumulation (historical or future rainfall) for four consecutive days before the occurrence of flood; a_1, a_2, a_3, ..., an are the ***R*** rainfall for day-1 until day-n (n = 1, 2, 3, ...,∞); and, b_1, b_2, b_3, ..., b_m are the $\boldsymbol{R_4}$ rainfall for day-1 until day-m (m = 1, 2, 3, ...,∞). Value of b_1, b_2, b_3, ..., bm can be defined as:

$$b_{n-8} = a_{n-8} + a_{n-2} + a_{n-1} + a_n \quad (3)$$

2. based on Equation 3 we can build the probability distribution model for the historical and future rainfall and compute the probability or return period of effective rainfall (R_4).

Table 1. Relationship between the historical or future rainfall and the rainfall accumulation

Rainfall data (mm)	Day								
	1	2	3	4	5	6	7	....	n
R	a_1	a_2	a_3	a_4	a_5	a_6	a_7	....	a_n
R4				b_1	b_2	b_3	b_4	....	b_m

2.4. Estimation of flood prone areas

The flood prone areas can be estimated from relation between data of the effective rainfall probability and location of flood inundation for each flood event. This relationship results in spread of flood prone areas for the historical and future rainfall conditions that can be mapped using GIS tool. Fig. 1 illustrates the technical steps in determining the flood prone areas at research area.

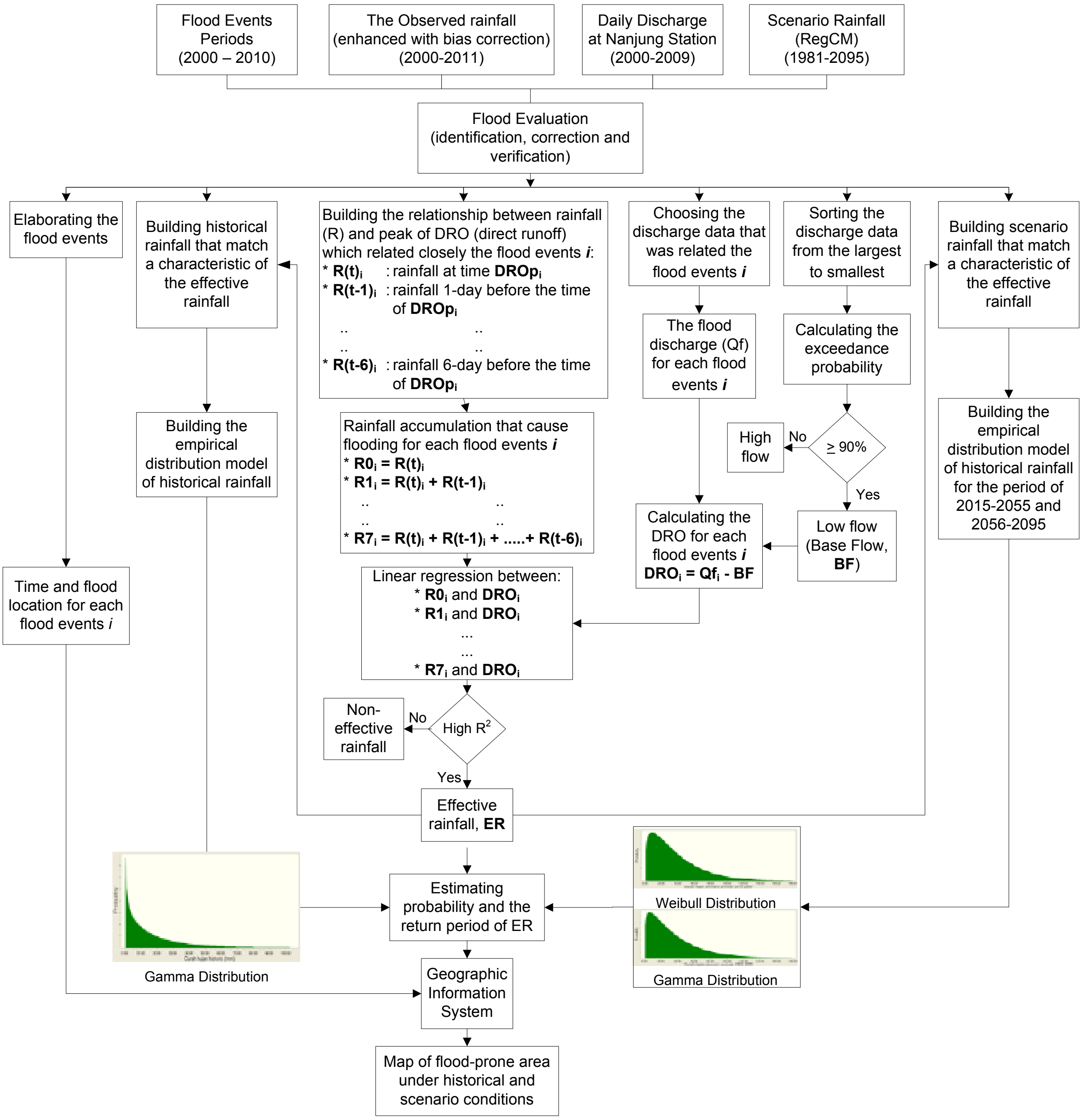

Figure 1. Flow the estimation and mapping of flood-prone areas according to historical rainfall and future rainfall for period of 2015-2055 and 2056-2095

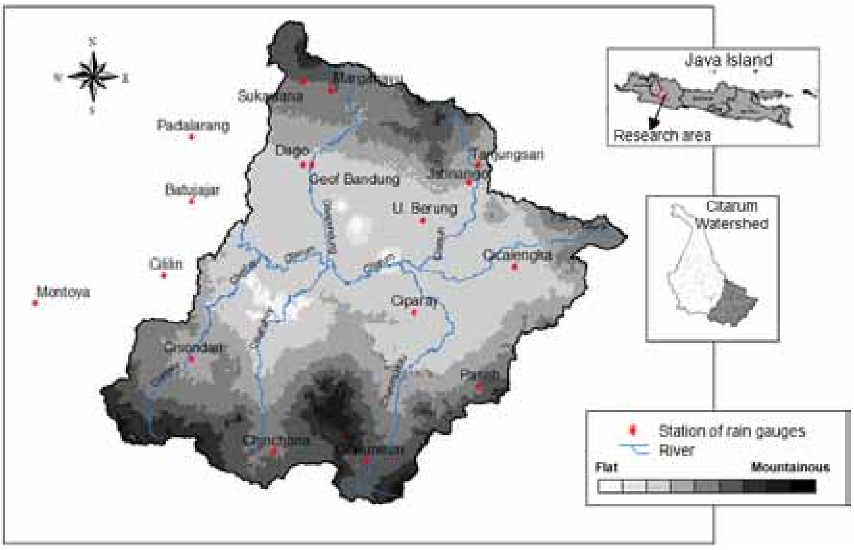

Figure 2. The topographic distribution and position of rain gauges on the Upper Citarum Watershed

2.5. Model validation

In this step, we will compare between the estimated flood extents and the actual one; and, the spread of actual flood is acquired from the satellite data (Landsat-7). Horritt and Bates (2002); Knebl *et al.* (2005) have used the following equation to examine accuracy of the estimated flood extents.

$$F = \frac{Num(S_{mod} \cap S_{obs})}{Num(S_{mod} \cup S_{obs})} \times 100\% \qquad (4)$$

where S_{mod} and S_{obs} are the numbers of pixel or cells predicted as flooded by the model and observed to be flooded in the satellite imagery; and, Num(.) shows the number of members of the set. Value of F varies between 0 and 100; value of 0 is no overlap between predicted and observed inundated areas and 100 will be achieved when result of model and the observed one coincide perfectly.

3. Results and Discussion

The Upper Citarum Watershed is located in West Java province, Indonesia. It stretches between 107.38°-107.95°E and 6.76°-7.26°S, covering a total area of 1802.7 km^2. This area is surrounded by hilly topography to mountainous but flat in the middle part (Fig. 2). It is due to such a topographic form that this region is vulnerable to flooding.

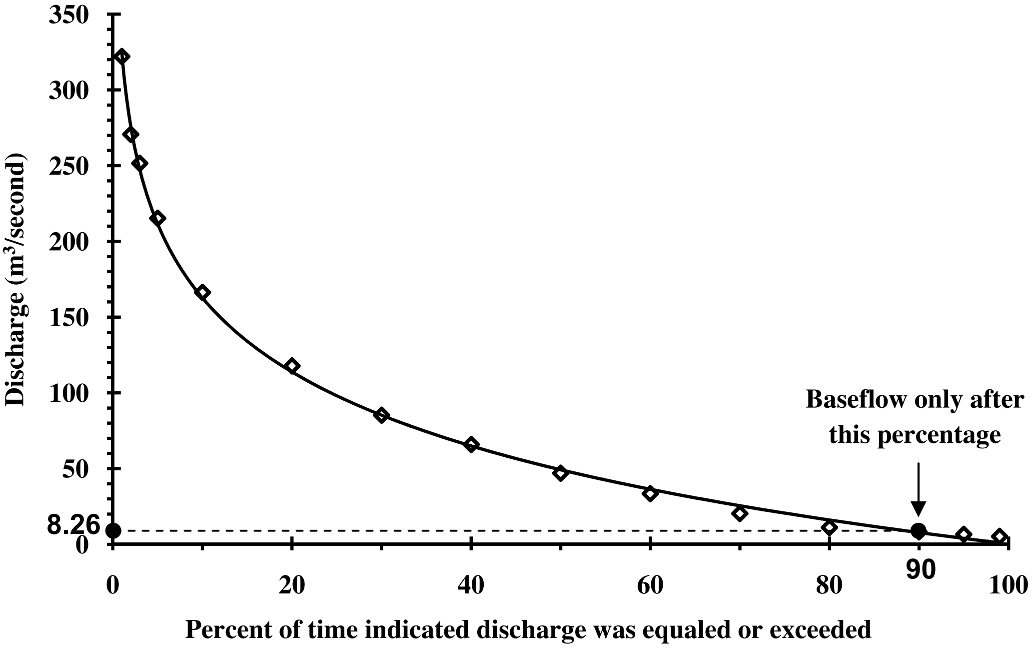

Figure 3. Flow duration curve in Upper Citarum River at Nanjung station (2000-2009)

3.1. Determination of effective rainfall

The effective rainfall is a rainfall excess that contributes to the occurrence of DRO resulting in flooding in the research area. DRO constitutes the yield of the subtraction between discharge and baseflow. Citarum River is the perennial stream so that magnitude of baseflow is assumed to be equal to the low flow. In this case, it can be estimated using the flow duration curve. The curve in Fig. 3 shows the duration of daily flow of Nanjung station (outlet of Upper Citarum Watershed) for 2000-2009. Fig. 3 shows that the slope of the lower end of the duration curve (i.e. the low flow portion) is almost flat; according to Searcy (1969) low flow in this condition is supplied by groundwater and this constitutes baseflow. Using Fig. 3 the baseflow in the research area is estimated to be about 8.26 m^{3}s^{-1} with probability of exceedance by 90%. Based on this data, DRO can be calculated for further analysis.

Fig. 4 describes relationship between DRO and scenarios of rainfall accumulation. using regression analysis. The accuracy of the models is measured based on coefficient of determination of the equations (R^2). R-squared is a statistical measure of how close the data are to the fitted regression line. In general, the higher the R-squared, the better the model is as long as the model assumption is fulfilled. The R^2 increased as the number of consecutive days used for calculating the rainfall accumulations reached four days and then it decreased (Fig. 4a-f). Based on this result, the regression model in Fig. 4e is chosen and used to predict the duration of effective rainfall causing flooding. With this simple equation, we can infer fastly the duration of effective rainfall causing floods. This simple equation is reliable

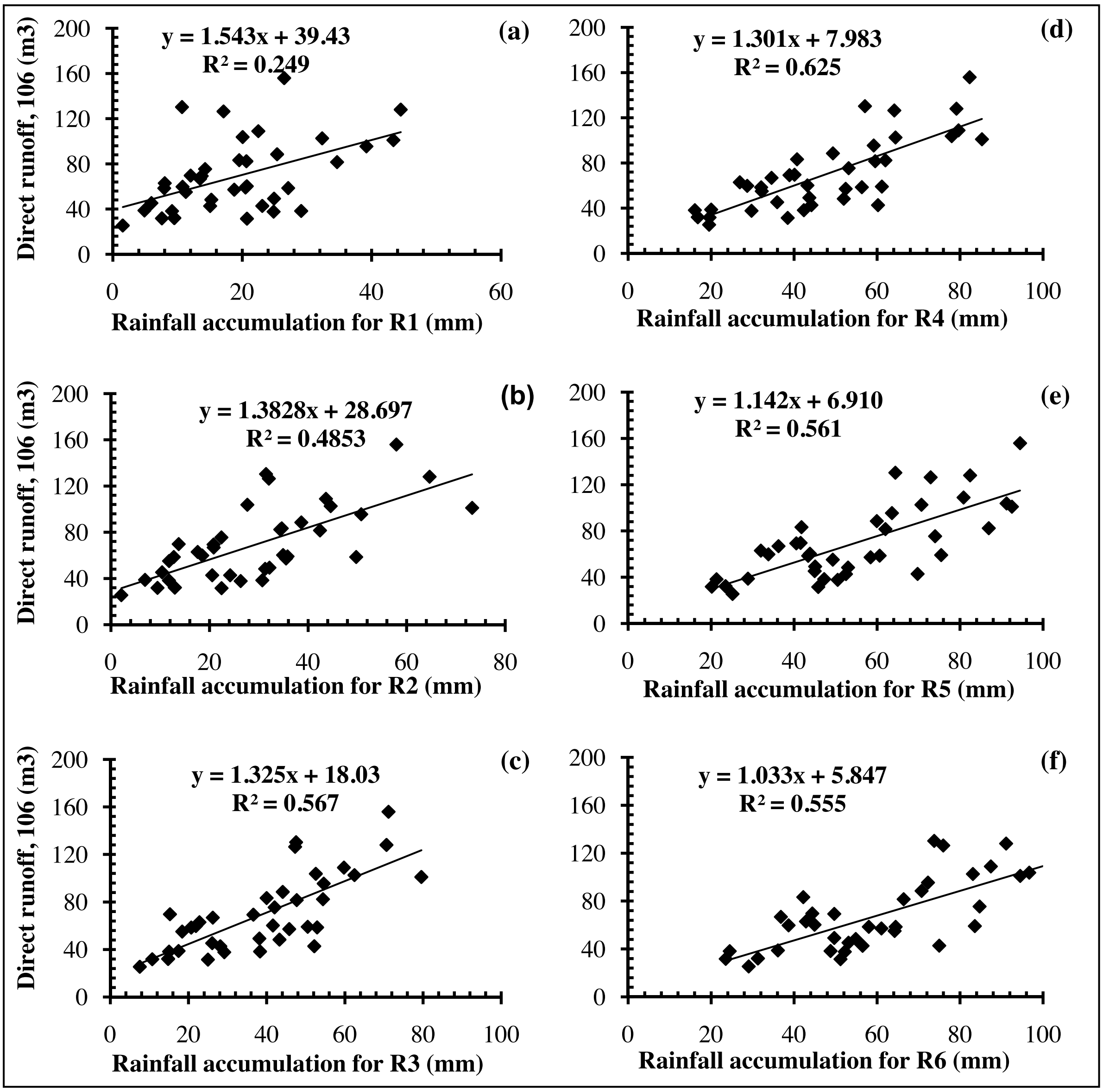

Figure 4. Correlation between direct runoff and scenarios of rainfall accumulation. R1 is the accumulated rainfall during 1 day before peak of direct runoff (DROp). R2 until R6 describe the accumulated rainfall during 2 to 6 days before DROp

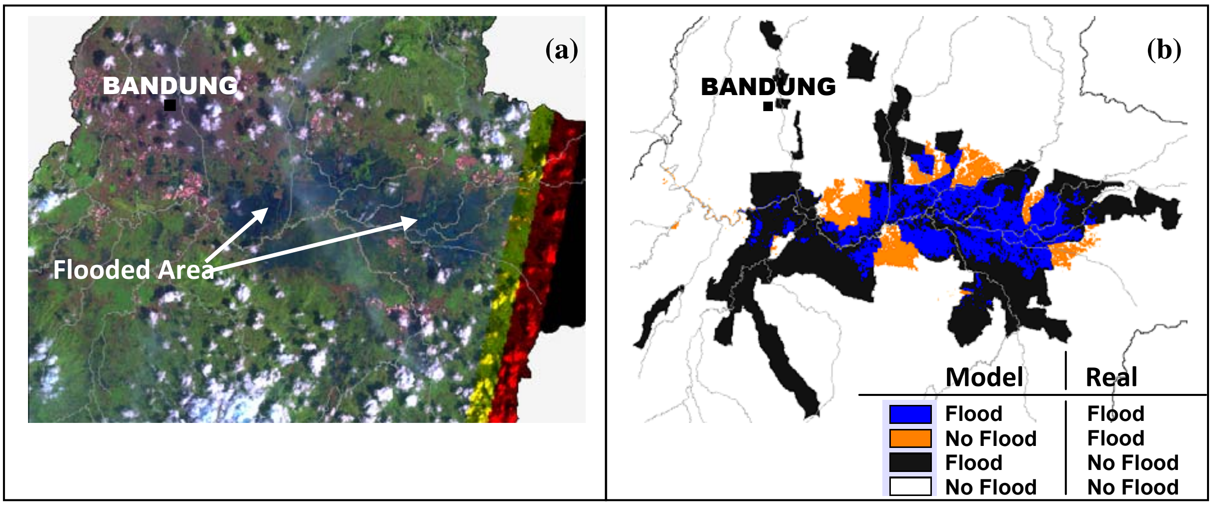

Figure 5. Comparison between the estimated flood extents and real (with return period of 25 year) in Upper Citarum Watershed. Fig. a was actual flood that was extracted from imagery of Landsat-7 (acquisition date: 7 January 2002). Fig. b was the superimposed imagery between the estimated (model) and real flood

enough since it has reasonable high R^2 and the model residuals have been tested to be randomly and normally distributed.

3.2. Mapping flood prone areas

Under rainfall conditions of historic and future (the period of 2015-2055 and 2056-2099), the empirical distribution model for the effective rainfall which fall in the research area is more toward the distribution models of Gamma, Weibull, and Gamma, respectively. Based on the effective rainfall (historical condition) and the Gamma distribution model, the estimated flood extents with the probability of occurrence more than 4% (25-year return period) reach more than 227 km^2. In the same period, the imagery of Landsat-7 has recorded the flood events on January 7, 2002 and the real flood extents achieve more than 91.4 km^2. Result of comparison between the estimated flood extents and the real one is about 76.9% (Fig. 5b, area with blue color). This proves that the method that is used in this study is reliable.

The advantage of this method is very simple because we only use a simple regression approach to determine the level of flood prone areas; and, the time consumption which is used to finish it is shorter than the use of hydrodynamic model. This method can also be used as a rapid appraisal to identify the location of flooding so that we can address flooding with a fast and accurate because this method is able to indicate the location and likelihood of flood events with detail. Beside reliability, this method contained some weakness, namely: (1) need a detailed flood information (such as flood-affected villages, date of flood events, a flood characteristic, and record of flooding in the long term) and if these data is not available then the extent of flooded areas cannot be mapped; (2) effect of landuse change can not be captured in phenomenon the changes of extents and spread of flood.

Based on the approach which was used in this method, the spread of flood prone areas under the historical and future rainfall condition can be identified and compared (see Fig. 6). As can be seen in Fig. 6a and Table 2, the flood prone areas with return period of 2-5 year is about 21 km^2. When there are climate changes (A1B scenario), this region is predicted to experience flood with return period of less than 2 year; and, flood extents will achieve about 39.9 and 21 km^2 in the period of 2015-2055 and 2056-2099, respectively (see Fig. 6b, 6c and Table 2). In large flood of 25-year return

Table 2. Flood extents according to the level of flood prone and the return period under historical and future rainfall conditions

Level of flood prone	Return period [yr]	Flood area (km^2)		
		History	2015-2055	2056-2095
Very high	< 2	0.00	39.90	21.00
High	2 - 5	21.00	191.65	191.65
Midlle	5 - 10	123.39	205.64	210.77
Low	10 - 25	191.65	227.25	227.25
Very low	> 25	227.25		

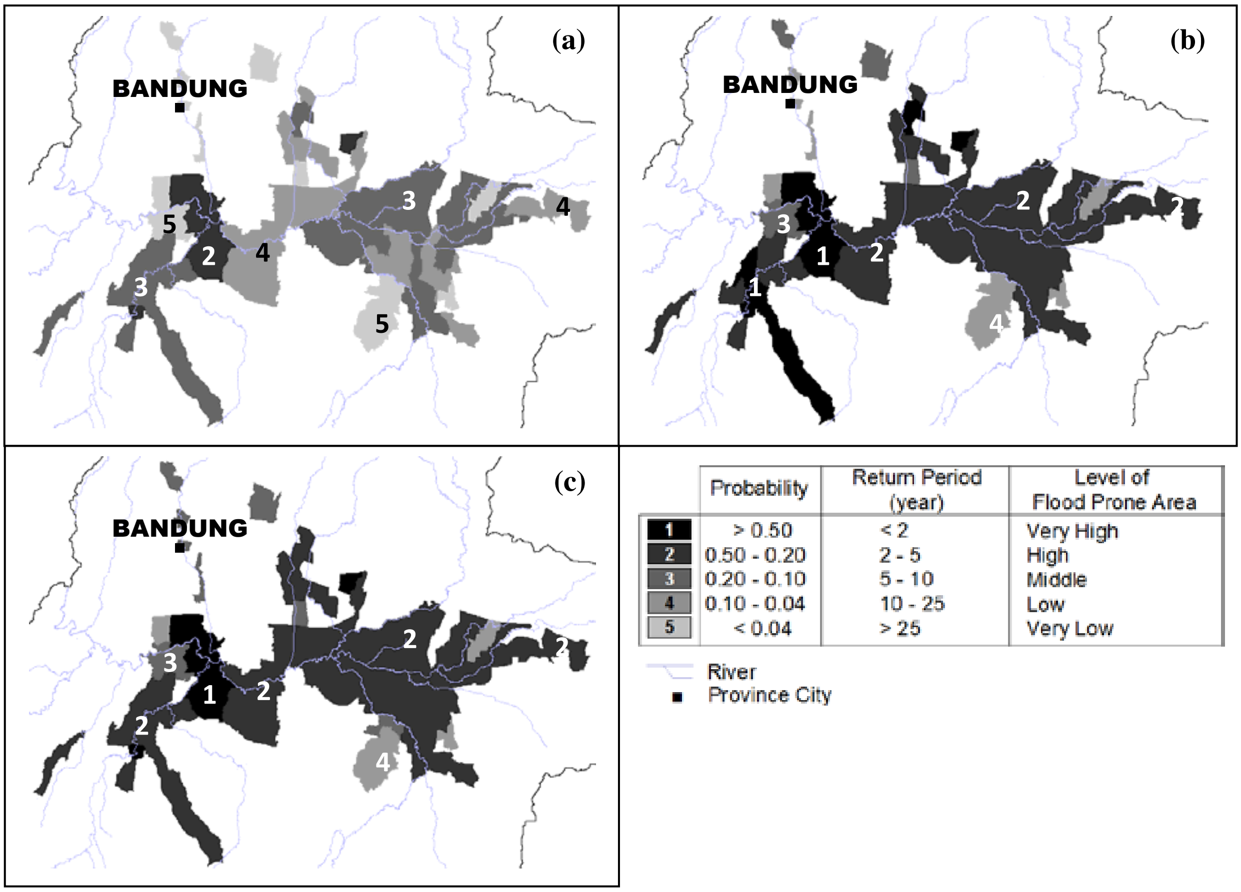

Figure 6. Flood prone areas based on the historical and future rainfall. (a) is flood prone area according to the historical rainfall. (b) and (c) are flood prone area for period of 2015-2055 dan 2056-2095

period, under historical condition the flood prone areas are predicted to spread to 28 sub-districts, covering 79 villages that reach more than 227 km^2. If there are climate changes, flood frequency for the large flood will increase to once in 10-25 year (see Table 2).

4. Conclusion

Effective rainfall can be estimated based on relationship between rainfall accumulation before peak of DRO and DRO volume for each flood event. The effective rainfall causing flooding in the study area is the rainfall accumulation for four consecutive days (R_4) before occurrence of peak of DRO (DROp). The relationship between the R_4 and DROp can be represented using simple regression model with $R^2=0.625$.

The simple regression model can be used to estimate probability of flood events at Cekungan Bandung along with the map of flood distribution areas using GIS techniques with reasonable accuracy. The percentage of accuracy between the estimated and actual flood areas was about 76.9%. Under future rainfall (A1B scenario), flood frequency in the research area will increase and the flood extents will go up significantly.

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