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DERIVATION OF THE CRITICAL RAINFALL LEVEL NEEDED FOR AN EARLY FLOOD WARNING IN THE UPPER CITARUM RIVER BASIN INDONESIA

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ABSTRACT: Rainfall is one of the common triggering factors of the flood. Bandung City is located in the Upper Citarum river basin. Parts of the city, such as Bojong Sari, Bojong Soang, Cieunteung and Andir Sub district, are in natural floodplains. During the wet season, these areas are frequently flooded. This study analyzed the critical rainfall level that potentially caused flooding. The Hydrologic Engineering Centres Hydrologic Modelling System (HEC-HMS) rainfall-runoff model and the 1D HEC-RAS model were applied. A six storm pattern was simulated to determine the critical rainfall that generated the water depth that was equal to or greater than the critical water surface depth at specific points in the river. Hypothetical rainfall events are used to investigate the response of the river basin at critical cross-sections. It can be considered by different temporal distributions. The amount of rainfall is assumed to be distributed uniformly. The conclusion of this research is that the storm pattern (rainfall depth and rainfall duration) plays a crucial role in determining the critical rainfall at the flood location. The critical rainfall in a specific location is affected by the position at the river cross-section (in the upstream or the downstream area) and the bank full capacity of the river cross-sections.

Keywords: Critical rainfalls, Flood, Upper citarum, River basin,

1. INTRODUCTION

Flooding is the most frequent hydro-meteorological disaster in Indonesia. Flood forecasting and early warning systems are important tools for reducing vulnerabilities and flood risks to populations who must “live with floods” [1]. Flood prediction is a critical aspect of the operational guideline of decision making. An early warning system for floods allows for instantaneous action from the regional authorities and the mitigation of the damage from projected major inundation and flooding in a floodplain [2]. Flood discharge is highly implicated in studies regarding water resource exploitation, basin management, flood control, construction of dams, and hydrologic studies. Therefore, the accuracy of these studies and the safety of waterworks and water structures are affected [3].

In the design of a hydrologic system, the rainfall data serve as the system input, and the resulting flow rates through the system are considered using the rainfall–runoff and flow routing procedures [4]. Design storm involves the important elements needed for a flood hydrograph. The components of design storm are rainfall duration, recurrence interval, and time distribution of the rainfall (hyetograph). During a rainfall event, a flood warning is a dynamic process that is updated frequently with rainfall information; flooding produced by the exceeding of short- and long-duration rainfall thresholds have different impacts in terms of emergency and severity [5].

Many related factors, such as the intensity and duration of rainfall, and the spatial scale and land use of the basin, should be considered in the peak flow. A storm with high rainfall intensity will generally produce a larger percentage of runoff than a similar storm with low rainfall intensity. The percentage of surface runoff increases as the total rainfall increases [6]. In the medium- and small-sized basins, intense rainfall can produce intensive and damaging flows that cause damage to properties and a loss of life in a very short time period [7].

Several methods for critical rainfall determination have been widely used for the purpose of flash flood early warnings. There are two methods as follows: the first method provides dynamic critical rainfall, and the second method is based on the typical design condition (design storm pattern, soil moisture content and fixed rainfall duration) [8]. The critical rainfall method was developed for use in a flash flood early warning system [9-11].

The objective of this work was to derive the critical rainfalls required for generating water depths equal or greater than the critical water surface depth at specific points in the river using the calibrated semi-distributed hydrological model and 1D hydraulic model HEC RAS 5.0.3.

2. MATERIALS AND METHOD

2.1 Description of Study Area

The Upper Citarum River Basin is located in the Bandung region of West Java province, and itis the upstream part of the catchment of the Citarum River and drains into Saguling Reservoir near Nanjung. The Upper Citarum River Basin covers a total area of 1,822.607 km^2, spanning from 107°15’36’’- 107°57’00’’ E, 06°’43’48” - 07°’15’00” LS. The Upper Citarum River basin is shown Fig. 1.

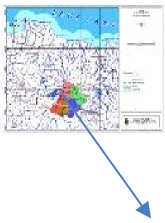

Fig. 1. Upper Citarum basin with tributaries

The Upper Citarum River Basin is divided into 12 sub-basins; the areas of the sub-basins are shown in Table 1. The Citarum river is the main river system drainage the catchment, the other minor rivers in the region are Citarik, Cikeruh, Cipamokolan, Cidurian, Cicadas, Cikapundung, Cisangkuy, Cibolerang, Ciwidey, and Cibeureum.

The meeting point of these tributaries and the main river form a bottleneck for the water flow, as it is located in a flat area. As a result, this flat area generates a natural floodplain area for its river basin. This natural floodplain covers Bandung City and Bandung Regency, where Rancaekek, Sapan, Baleendah, and Dayeuh Kolot Subdistricts are located. The downstream of upper Citarum River consists of the hilly area, which provides an area of high potential for reservoir development [12].

Table 1. Sub-Basin Areas

Sub Basin	Area (km^2)
Cicadas	28.108
Cidurian	33.903
Cikapudung	144.687
Cikeruh	179.448
Cipamokolan	43.244
Cisangkuy	285.134
Citarik	286.808
Citarum	346.370
Cimahi	65.639
Cibeureum	131.757
Cibolerang	60.776
Ciwidey	216.732
Total	1822.607

The dominant land cover in the Upper Citarum River Basin consists of dry crops (26%), rice fields (23%), and resident area (20%). The major soil types of the study area are Latosol (36%), Andosol (30%), and Alluvial (20%).

2.2 Rainfall Data and Analysis

Hourly rainfall data were used in this research for the calibration model. There are 13 automatic rainfall gauges in the Upper Citarum River Basin with hourly rainfall (Fig. 2).

Extreme rainfall events in the Upper Citarum typically have a convective origin. The highest rainfall intensities are observed from 12:00 to 19:00 hrs. The average rainfall duration, which is dominant in Upper Citarum River Basin, is approximately 5 hours. Fig. 3 shows the temporal rainfall distribution.

Fig. 2. Location of automatic rainfall stations

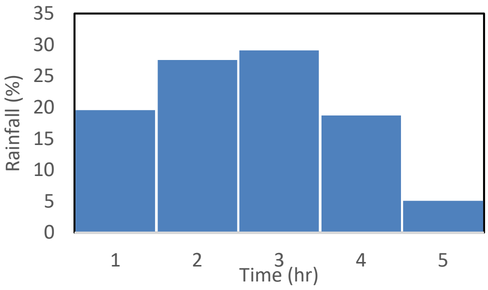

Fig. 3. Rainfall distribution

2.3 HEC-HMS Hydrological Model

The Hydrologic Engineering Centers Hydrologic Modelling System (HEC-HMS) is a hydrologic modeling software developed by the US Army Corps of Engineers (USACE) Hydrologic Engineering Centre (HEC). HEC-HMS is a numerical model (computer program) that includes a large set of methods to simulate watershed, channel, and water-control structure behavior, thus predicting flow, stage, and timing [14].

To increase the modeling performance, the catchment is split into sub-basins to use the model in a semi-distributed manner. There are 8 sub-basins analyzed, namely, Citarum Hulu, Citarik, Cikeruh, Cidurian, Cicadas, Cipamokolan Cisangkuy, and Cikapundung (Fig. 4). Initial catchment parameters are shown in Table 2. The SCS curve number method was used to compute the losses, and the SCS Unit hydrograph was used in the transform method to estimate surface runoff and total runoff.

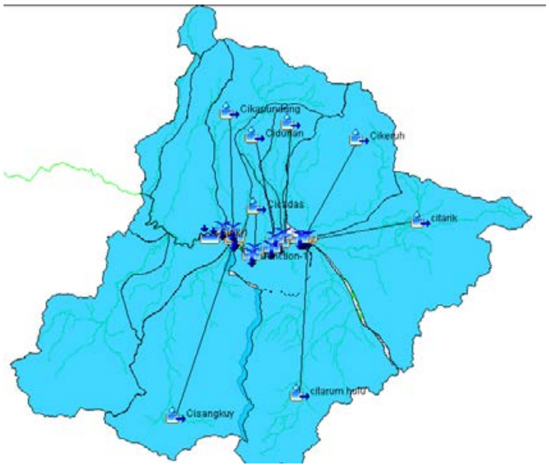

Fig. 4. Sub-basin model

Table 2 Initial catchment parameters

Sub Das	Area (km2)	CN	Impervious (%)	Lag time (minute)
citarum hulu	346.37	68.50	2.37	299.22
citarik	286.81	64.02	5.62	287.4
Cikeruh	179.45	63.18	11.99	219.6
Cipamokolan	43.24	61.83	15.27	219.6
Cidurian	33.90	71.46	17.50	221.34
Cicadas	28.11	67.86	19.94	219.6
Cikapundung	144.69	61.19	13.29	295.2
Cisangkuy	285.13	65.35	3.61	260.52

2.4 Calibration of the Model

The objective of the model calibration is to match the observed simulated runoff volumes, runoff peaks and timing of hydrographs with the observed ones. The calibration model is used to obtain the specified condition concerning the analyses in the basin. The HEC-HMS watershed model is calibrated for the event-based simulation. Three events floods were selected for model calibration (Table 3 and Figs. 5-7). The considered initial parameter values are first used in the HEC-HMS model for calibration, and different parameters, such as runoff depth and peak discharge, are simulated. The initial calculated parameters are then optimized using the optimization tool available in the HEC-HMS model, the optimized parameters are shown in Table 4. Figs. 8-10 show a comparison of the simulated and observed hydrographs for the three events. These figures disclose that the simulated runoff hydrograph is close to the observed one for all the events.

Table 3 Flood events for calibration

No.	Flood Events (Date)
1	27th February 2017 12:00 to 28th February 2017 12:00
2	7th March 2017 09:00 to 9th March 2017 09:00
3	22nd April 2017 12:00 to 23rd April 2017 12:00

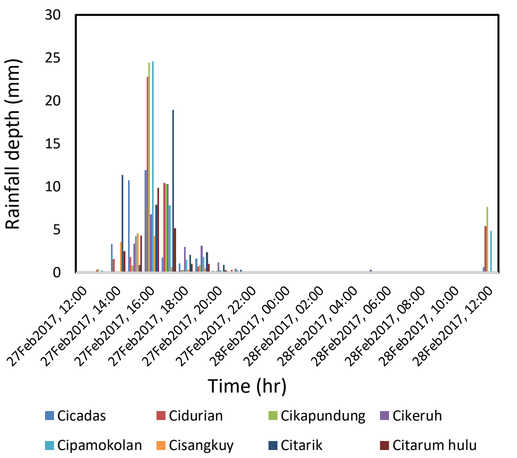

Fig. 5. Hyetograph of flood events 27th February 2017 12:00 to 28th February 2017 12:00

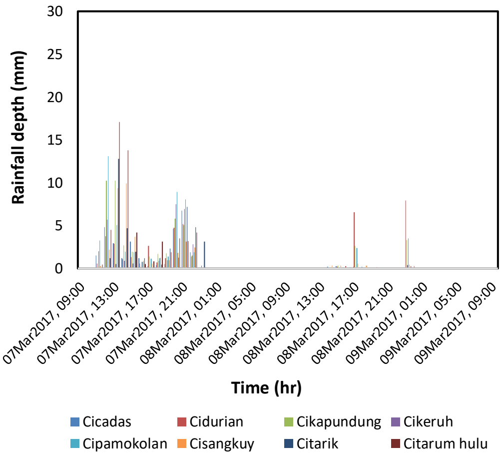

Fig. 6. Hyetograph of flood events 7th March 2017 09:00 to 9th March 2017 09:00

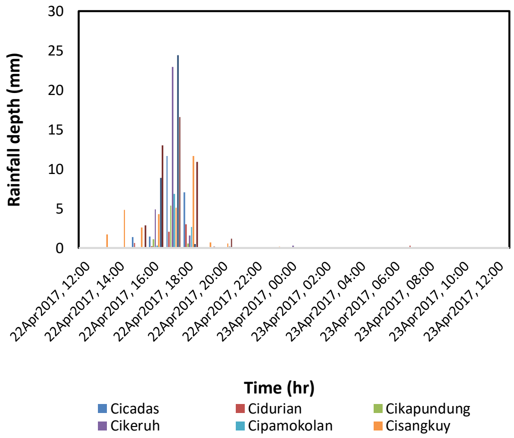

Fig. 7. Hyetograph of flood events 22nd April 2017 12:00 to 23rd April 2017 12:00

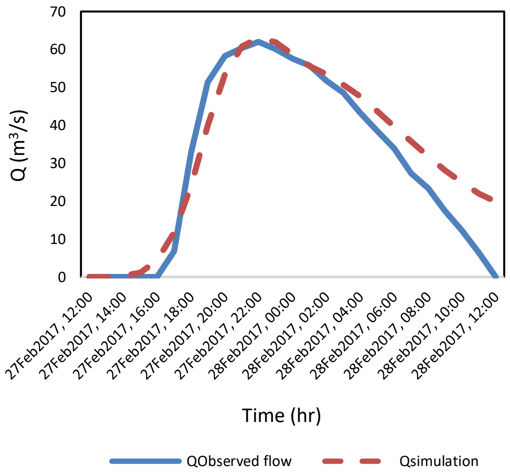

Fig. 8. Simulated and observed hydrograph of flood events 27th February 2017 12:00 to 28th February 2017 12:00

Table 4 Optimized parameters

Element	Initial Abstraction (mm)	CN	Routing Parameter	
			K (hr)	X
Citarum hulu	23.448	57.611		
Citarik	28.689	62.736		
Cikeruh	29.447	73.295		
Cipamokolan	31.464	61.002		
Cidurian	20.346	73.739		
Cicadas	24.093	66.967		
Cikapundung	32.323	60.371		
Cisangkuy	27.017	64.479		
Reach-1			0.088	0.154
Reach-2			4.527	0.175
Reach-3			0.268	0.154
Reach-4			2.146	0.175
Reach-5			1.706	0.175
Reach-6			0.204	0.154

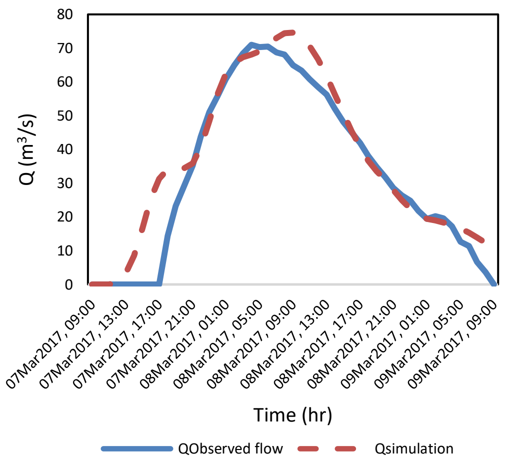

Fig. 9. Comparison of the simulated and observed hydrograph of flood events 7th March 2017 09:00 to 9th March 2017 09:00

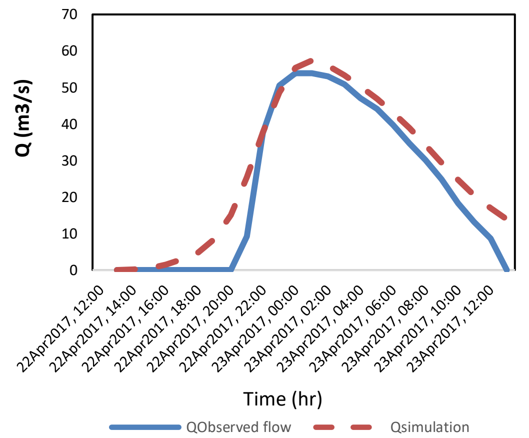

Fig. 10. Comparison of the simulated and observed hydrograph of flood events 22nd April 2017 12:00 to 23rd April 2017 12:00

2.5 Model Performance Criteria

The model performance is assessed for calibration by different methods, as well as for Nash-Sutcliffe efficiency ENS, and R^2. These criteria are used to evaluate the hydrological modeling performance.

$$\boldsymbol{R^2} = \left(\frac{\Sigma(Q_{obs}-\overline{Q_{obs}})^2-\Sigma(Q_{sim}-\overline{Q_{sim}})^2}{\Sigma(Q_{obs}-\overline{Q_{obs}})^2}\right) \quad (1)$$

$$\boldsymbol{ENS} = 1 - \frac{\Sigma(Q_{obs}-Q_{sim})^2}{\Sigma(Q_{obs}-\overline{Q_{obs}})} X100 \quad (2)$$

Where:
Qobs = observed discharge
Qsim = simulated discharge
Obs = mean of observed discharge
Sim = mean of simulated discharge

Nash-Sutcliffe efficiencies can range from -∞ to 1. An efficiency of ENS=1 signifies a perfect match of the modeled discharge to the observed data. The following model presentation involves the study of the suitable performance of the model calibration. The values of the model performance criteria are shown in Table 5. Nash-Sutcliffe defines the similarity in the value of the discharge from the modeling result compared to the observed discharge. If the value is close to one, then the discharge of the modeling result has a similar pattern to that of the observed discharge.

Table 5 Model performance for calibration

Flood Events	NSE	Coefficient Correlation (R^2)
27th February 2017 12:00 to 28th February 2017 12:00	0.896	0.959
7th March 2017 09:00 to 9th March 2017 09:00	0.890	0.957
22nd April 2017 12:00 to 23rd April 2017 12:00	0.739	0.965

3. RESULTS

3.1 Storm Pattern

Storm patterns are conducted to identify the rainfall that causes the critical discharge or critical water surface in a specific river cross-section. In this research, four critical river cross-sections are chosen in the areas where more frequent flooding occurs (Fig. 11). Fig. 11 shows the flooded region can be divided into four spatial locations, namely, Bojong sari, Bojong Soang, Cieunteung, and Andir.

The response of the basin to the critical cross-section is investigated using hypothetical storm temporal distribution events for various cumulative rainfall values and durations and can be characterized by different temporal distributions. The amount of rainfall is assumed to be distributed uniformly; this study adopts rainfall by the durations of 2-, 3-, 4-, 5- and 6-h. The evaluation the critical rainfall is required to generate devastating surface runoff under the durations of 2-, 3-, 4, ,5- and 6-h. The numerical analysis is accompanied by iteratively presenting different rainfall hyetographs into the HEC HMS rainfall-runoff model and the 1D HEC RAS model to determine the critical rainfalls required for producing water depth equal or greater than critical water surface at the specific points in the river. The critical water level in each point is shown in Table 6.

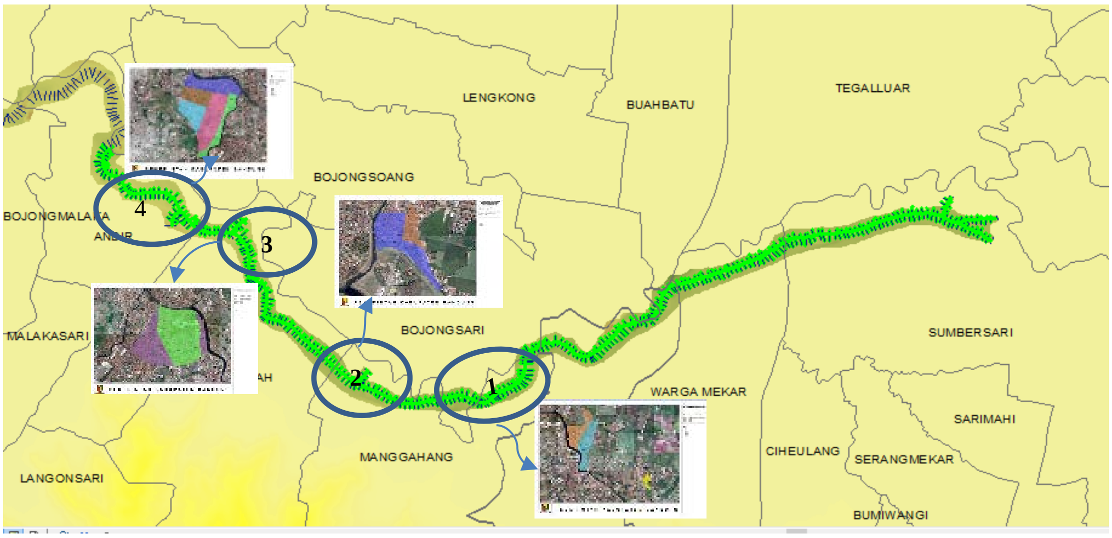

Fig. 11. Flood location

Table 6 Critical water levels at the flood location

Flood location	River Cross-Section	Critical Water Level (m)
1 (Bojong sari)	142	4.30
2 (Bojong Soang)	70	4.65
3 (Cieunteung)	17	2.24
4 (Andir)	4	4.27

Six storm patterns are generated based on the hydrological responses for rainfall events at fixed cumulative values and durations. Six different values of cumulative rainfall, R_c, are chosen between 10 mm and 55 mm. Each of the Rc values is then used to create 5 events of different durations, d, varying from 2 to 6 hours, with an hourly time-step.

3.2 Critical Rainfall

Critical rainfall derived from six storm patterns at four specific cross-sections. The simulations are performed in HEC RAS 5.0.3 with unsteady state condition to generate the profiles of the water surface. Figs. 12-16 present the profiles of the maximum water surface in the fourth river cross-section (RS-142, 70, 17, and 4).

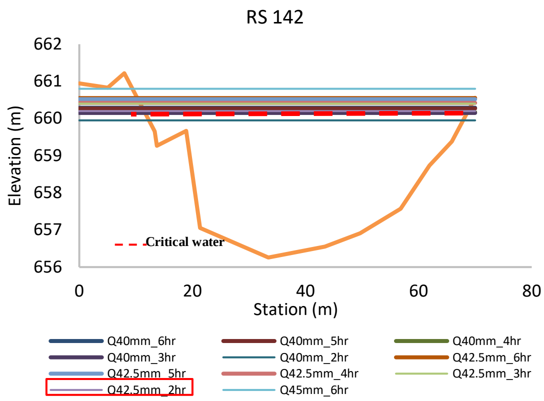

Fig. 12. Profile of the maximum water surface in RS-142

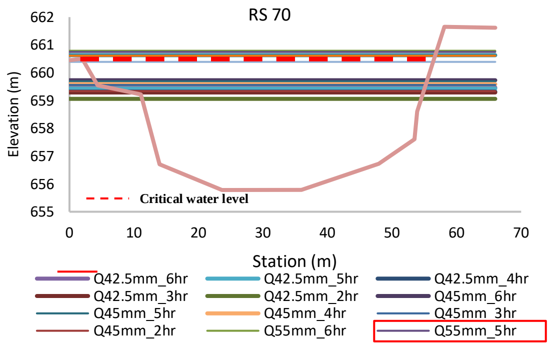

Fig. 13. Profile of the maximum water surface in RS-70

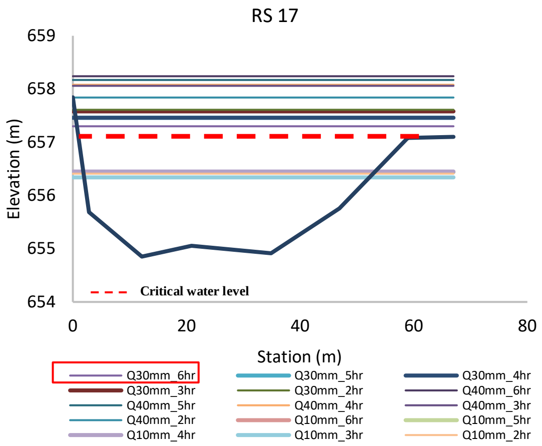

Fig. 14 Profile of the maximum water surface in RS-17

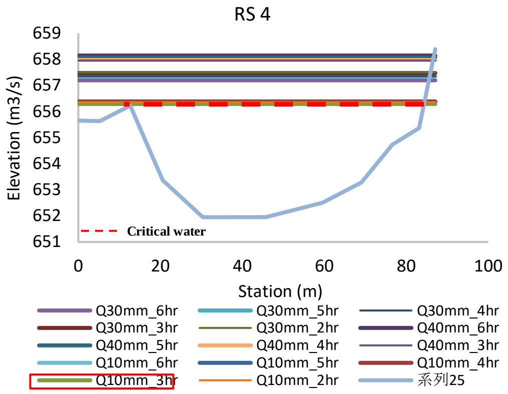

Fig. 15 Profile of the maximum water surface in RS-4

The critical rainfall level is acquired when the simulated water surface remains equal to the critical water level. Table 7 indicates the critical rainfall in each location. Fig.16 shows a comparison of the relationship between the rainfall durations and the cumulative rainfall for the four critical river cross-sections.

Table 7 The Critical Rainfall

Flood location	River Cross-Secti-on	Critical Rainfall	
		24-hr Rainfall Depth (mm)	Durati-on (hr)
1 (Bojong sari)	142	42.5	2
2 (Bojong Soang)	70	55	5
3 (Cieunteung)	17	30	6
4 (Andir)	4	10	3

It can be seen that flooding in the Bojong Sari area (RS 142), which is located in the upstream, was triggered by a high rainfall depth and a short duration. In contrast, the flooding in the downstream area (Andir/RS 4) is produced by the lowest rainfall depth.

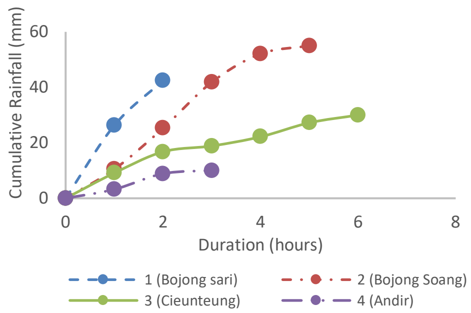

Fig. 16 Comparison of the relationship between the cumulative rainfall and the rainfall durations at the four critical river cross-sections

4. CONCLUSIONS

The aim of this research was to obtain the critical rainfall as a trigger of flooding in the Upstream Citarum river basin. Numerical experiments were conducted by iteratively introducing different rainfall hyetographs into the HEC HMS rainfall-runoff model and the 1D HEC RAS model to determine the critical rainfall levels required for generating a water depth equal to or greater than the critical water level at specific points in the river.

The simulation used hypothetical rainfall events to allow for the consideration of cumulative rainfall value and duration, as well as different temporal distributions. In the simulation, the amount of rainfall is assumed to be distributed uniformly. The HEC-HMS model is used for the simulation of the runoff hydrograph in the Upper Citarum River Basin, Indonesia. The initial parameter is derived from the river basin characteristic. Using an optimization technique, the final calibration parameters were derived and considered as global values for the model. The results based on the Nash Sutcliffe model efficiency coefficient, coefficient correlation, and graphical evaluation showed that the HEC-HMS model is well suited for the simulation of the rainfall-runoff of the Upper Citarum River Basin, regardless of the sub-basins scale.

The critical rainfall levels produced at the four specific river cross-sections have different amounts of accumulated rainfall and different lengths of duration. Flooding at the Bojong Sari area (RS 142) located in the upstream is generated by a high rainfall depth and short duration. In contrast, the flooding at the downstream area (Andir/RS 4) is produced by the lowest rainfall depth. However, this research was based on hypothetical rainfall with simplified versions of both temporal and spatial rainfall distributions. Calibration and validation are required for historical flood data, and further analyses are necessary.

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