

Flood Quantification Index Based on Inundation Indicators and Risk Scale

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Abstract— Flood management requires an assessment of flood levels that occur appropriately. Determining flood levels quantitatively can help control floods more efficiently. This study aims to make flood quantification based on the inundation indicators and scale of risk. The case study is in Citarik, Cilember, Cimahi, Cisangkan, and Cibeureum, located in the Citarum watershed, West Java, Indonesia. The method used is a mathematical model of flow verified by the river's physical dimensions. Four indicators were analyzed based on unsteady one-dimensional river flow and overland flow models. The four flood quantity indicators with different weights are namely percentage of inundation area (Ai), percentage of area activity on the inundation area (Aac), inundation duration (D), and inundation depth (H) which have consecutive indexes 0.3, 0.2, 0.2 and 0.3. The initial discharge was analyzed based on unit hydrograph at the upstream river cross-section of the inundation region. The study's results by verification of field observations showed that the highest peak inundation was 3.0 m in Cilember, inundation duration was a maximum of 18 hours in Citarik and Cilember, the highest inundation area was 329.23 % of the watershed area of Cilember. Results of calculations with the formulations, the highest quantity is 16.18 in Cilember flood that occurs in Melong village with a risk scale of 5. These results conclude that the Cilember flood is high-level damage so that it is a priority to be overcome.

Keywords— Flood quantification; flood risk; inundation area; overland flow; unsteady one-dimensional flow.

Manuscript received 28 Aug. 2019; revised 29 Nov. 2020; accepted 24 Dec. 2020. Date of publication 30 Apr. 2021.
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I. INTRODUCTION

Floods are disasters that occur in many countries in the world, including Indonesia. Floods are caused by human factors and natural factors, for example, if humans live on the banks of floods. The danger of flooding depends on the flood's magnitude, such as inundation depth, inundation area, and inundation duration. Vulnerability can be defined as a condition determined by physical, social, economic, and environmental factors that increase a community's weakness to the impact of hazards. Floods that afflict communities and infrastructure result in vulnerability for both of which determine the level of damage. The impact of urban flooding is significant on both direct and indirect economic losses. [1]

Increased population, industrialization, and technological developments will increase the likelihood of flooding. Therefore, the careful implementation of resource management in the watershed is essential. Therefore, watershed management technology is needed to resolve

supply conflicts and drought problems [2]. Changes in land use can cause several negative impacts on the potential conditions and environment of estuarine water resources, such as floods, droughts, landslides, water pollution by pollutants, and sedimentation [3]. Changes in land use also resulted in changes in a water system and affected increasing the runoff coefficient and flooding [4],[5].

A. Flood Risk Mitigation Strategies in Several Countries

Prevention of flood hazards in the province of Izmir, Turkey, was carried out by detecting potential flood areas using the Shuttle Radar Topography Mission-Digital Elevation Model (SRTM-DEM). Five parameters were used: accumulation of discharge, land use, slope, rainfall intensity, and elevation to detect floods' spatial distribution. Each of these parameters is given quantification weight so that there are five qualification levels, namely very low, low, medium, high, and very high [6]. The Flood Risk Index Map was developed to estimate flood hazards and vulnerabilities in

the Bukit Duri sub-district, Tebet District, Jakarta, in the upper reaches of the Manggarai Watergate. The flood hazard index was analyzed based on inundation maps verified with field data. Based on the research risk map, the study area is a high-risk flooding area due to dense population housing and inadequate flood mitigation [7].

Flood risk mitigation strategies in the Niger Delta, coastal areas of Nigeria, apply flood control with structural and non-structural methods. Non-structural methods are behavior adjustments for flood control. The study observes that in order for flood risk mitigation strategies to be effective in the Niger Delta, it is necessary to establish coastal management zone authorities, land-use zoning, laws, building codes, flood forecasts, and warning systems, flood insurance, and engineering of major river systems[[8].

Gorganroud watershed in the Golestan province of Iran conducted flood risk assessments using appropriate tools, such as Landsat ETM+ imaging and digital elevation model data collection in geographic information systems throughout the region. With the overlay and weighing three layers in the GIS software, the flood hazard's intensity layer is obtained. These two flood layers are coated with the help of a two-dimensional matrix, and a final flood risk map is obtained. Finally, it was found that Chelichay and Gorganroud Sarab, which constitute 24.59% of the Gorganroud watershed, are the riskiest sub-watersheds [9].

B. Flood Risk Quantification Analysis Model

The main factors that must be considered in flood events are the great responsibility of flood mitigation in urban spatial planning, comprehensive community property mitigation, improved coordination, and disaster response through flood early warning, targets in flood disaster management. Risk control, namely climate change, land-use change, economic growth or demographic change, and total risk, must be investigated continuously [10].

Flood risk quantification analysis models are analyzed from watershed parameters such as design rainfall, design flood discharge (Q_{flood}), discharge capacity (Q_{capacity}), topography, and land-use map. Flood characteristics are determined by inundation indicators using one-dimensional unsteady flow models and overland flow. Risk calculation is determined based on demographic data, the percentage of activity areas to inundation areas. The flood quantification formula is calculated using the parameters above with different weights according to the flood's effect. The following schematic analysis of flood risk quantification is illustrated in figure 1, Model Analysis of Flood Risk Quantification. This model consists of six stages of the process: Base Analysis, Base Map, Inundation Process, Risk Process, Flood Quantification Process, and Final Results.

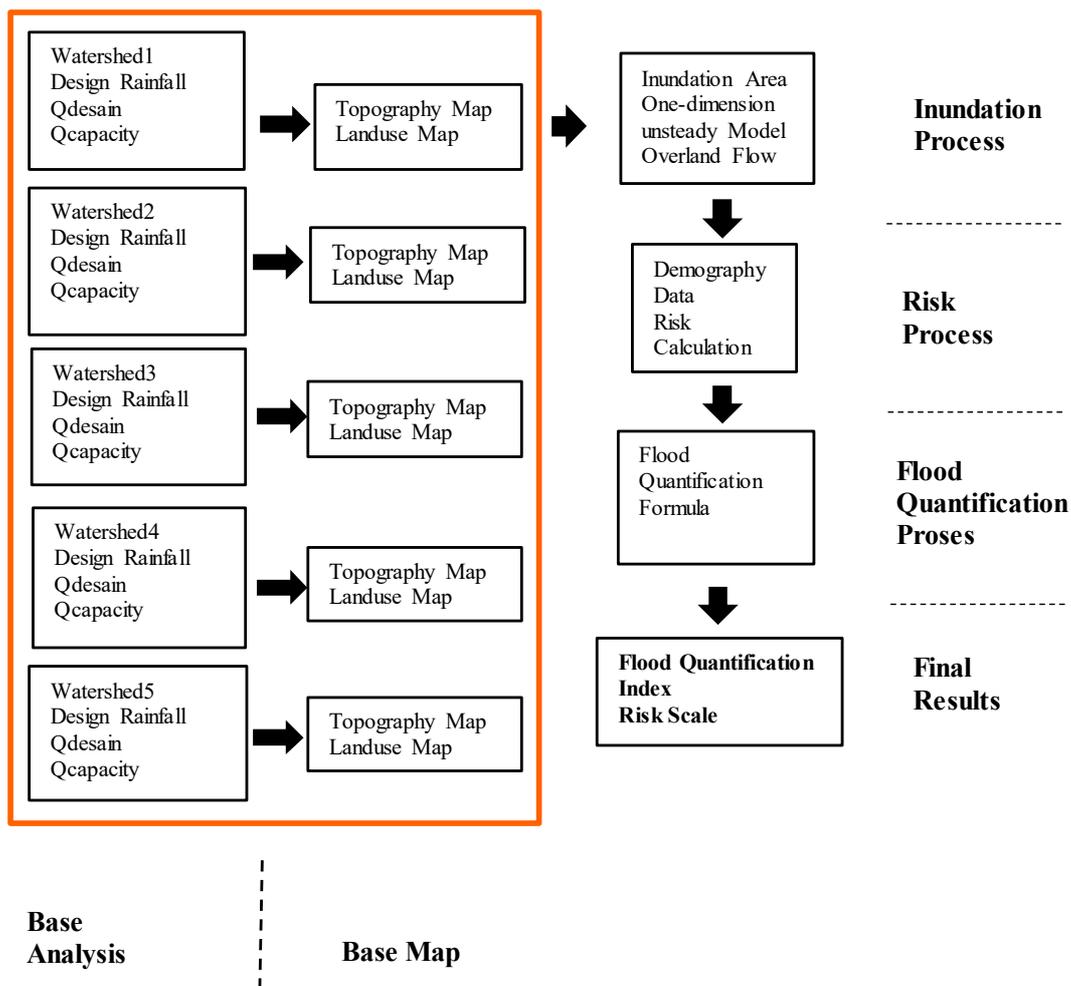


Fig. 1 Model Analysis of Flood Risk Quantification

A unit hydrograph is derived using Nakayasu synthetic method for average scale watershed, which has been calibrated based on the watershed characteristics [11]. The equation of peak discharge is shown in Equation 1 below.

$$Q_p = \frac{0.99AR_o}{3.7(0.1T_p + T_{0.3})} \quad (1)$$

Peak discharge (Q_p) is the function of watershed area (A), watershed characteristic coefficient ($C = 0.99$), unit rainfall (R_o), time lag (T_p) and time required to discharge reduction up to 30% peak discharge ($T_{0.3}$).

Load discharges are calculated based on design rainfall that is multiplied convolutive (Equation 2) after being converted into effective rainfall [12],[13]. Design rainfall is calculated using Gumbel frequency analysis while effective rainfall is calculated using a runoff coefficient derived from the land use map.

$$Q_n = \sum_{m=1}^{n \leq m} P_m U_{n-m+1} \quad (2)$$

Q is direct runoff discharge, P is effective rainfall, U is unit hydrograph ordinates, m is the adequate rainfall number, and n is the direct runoff discharge number. The inundation parameters analyzed were the inundation area, inundation duration, and inundation height. This variable is determined based on a one-dimensional unsteady model (Equation 3) for flow in the river and overland flow for overflow water from the river to the land, assuming after the water overflows into the land, the flow is uniform [14].

$$\frac{\partial y}{\partial x} + \alpha \frac{V}{g} \frac{\partial V}{\partial x} + \frac{1}{g} \frac{\partial V}{\partial t} + \frac{\partial z}{\partial x} + S_f = 0 \quad (3)$$

Where y is the flow depth, V is velocity, z is the distance of the bed channel from the datum, and S_f is the energy slope. All unit of variables is in the SI unit.

C. Formulation of Flood Quantification

The Flood quantification (K_f) formulation uses formulations with 4 indicators, namely percentage of inundation area (A_i), percentage of the area of activity on the inundation area (A_{ac}), inundation duration (D), and inundation depth (H) which have consecutive indexes respectively 0.3, 0.2, 0.2 and 0.3 [15] as are shown in equation 4. The flood quantification analysis is shown in Table 1.

$$K_f = 0.3 A_i + 0.2 A_{ac} + 0.2 D + 0.3 H \quad (4)$$

TABLE I
FLOOD QUANTIFICATION FORMULA

Risk Scale	% Inundation Area of Watershed	% Activity of Inundation Area	Inundation Duration (hour)	Inundation Depth (m)
	(A_i)	(A_{ac})	(D)	(H)
1	< 20	< 20	< 6	< 1
2	20 - 40	20 - 40	6 - 12	1 - 1.5
3	40 - 60	40 - 60	12 - 18	1.5 - 2
4	60 - 80	60 - 80	18 - 24	2 - 2.5
5	> 80	> 80	> 24	> 2.5

D. Classification of Flood Quantification Level

The scale of risk and quantity of flood, K_f , shows the level of damage that occurred. The lowest risk scale is scale 1, and the quantity of floods 1 to 2 where the inundation area that occurs is smaller than 20% of the watershed area, the area of activity is smaller than 20% of the watershed area, the duration of inundation is less than 6 hours, and the inundation height is less than 1 m. Flood quantity levels and risk scales are categorized as follows,

TABLE II
FLOOD QUANTIFICATION LEVEL

Quantity of Risk	Quantity of Flood (K_f)	Category	Level of Damage
1	$1 \leq K_f < 2$	Very Low	Very low damage
2	$2 \leq K_f < 4$	Low	Low damage
3	$4 \leq K_f < 6$	Medium	Damage
4	$6 \leq K_f < 8$	High	High Damage
5	$K_f \geq 8$	Very High	Very High Damage

II. THE MATERIAL AND METHOD

The method used in this study is a mathematical model of flow verified by the river's physical dimensions. Four indicators were analyzed based on unsteady one-dimensional river flow models and overland flow models for river overflows. This study applied a one-dimensional unsteady flow model (HEC-RAS software). An overland flow was calculated to analyze flow in the land using ArcGIS software, while a rainfall-runoff model is analyzed to determine flood discharge that is compiled by the convolution method (Matlab software). This research consists of four stages, as follows:

- Determine unit hydrographs.
- Determine load discharge based on design rainfall.
- Determine inundation area.
- Determine the quantity of flood and scale of risk.

The study was done in Citarik, Cilember, Cimahi, Cisangkan and Cibereum river that is in Citarum watershed, West Java, Indonesia.

In this research, all river flood inundation area occurs in the confluence area of the river. Rancaekkek sub-district is located in the branch area of Citarik river and Citarum river. In this area, there is also a meeting location of Citarik river with its tributaries; those are Cimande river and Cikijing river. Such a river meeting area is prone to flooding as happened in floods in the Melong village of Cimahi city in the branch area of Cilember and Cibereum river with Citarum river [16]. The meeting cross-section of Cisangkan river and Citarum river is in Leuwigajah Village, Cimahi City.

A. Area of Study and Rainfall Data

Citarik River is a second-order river that empties into Citarum river in Rancaekkek district of Bandung Regency at the geographical coordinates of 107.940 East and 6.960 South of 616.81 m MSL. Citarik River has a length of 51.8 km and its upper reaches in South Sumedang, Sumedang district at coordinates 107.7° East and 6.99° South at elevation 1210 m MSL. The watershed area is 332 km² with

an average slope of 8.7%. The average slope in the downstream area of Citarik tends to be flat, which is 1.1%, which is the meeting area of the Citarik tributaries such as Cikijing river and Cimande river which is the flood area of Rancaekek subdistrict.

The city of Cimahi is located in upstream of Citarum River as a part of Bandung Basin and one of the Citarum River valleys. The river that passes through the City of Cimahi is Cimahi River, Cibeureum river, Cibaligo (or Cilember) river, and Cisangkan River. The upstream of all these rivers are in Lembang at an elevation around 1450 m MSL, and the downstream is in the Citarum river near Saguling reservoir. Other characteristics of these rivers, the flow is through 3 cities, namely, West Bandung Regency in the upstream, Cimahi city in the midstream, and Bandung district in the downstream. Flooded areas are middle and downstream of those rivers.

B. Determine Load Discharge Based on Design Rainfall

Design rainfall was calculated with an 80% probability of wet years based on maximum daily rainfall data of Citarum Watershed for 2008-2017. Design adequate rainfall was calculated based on the runoff coefficient obtained from the land-use map and used for determining load discharge.

C. River Flood Quantification

In this study, the determination of the flood quantification was done by the watershed's physical approach, such as the area of inundation, land use map, topography map, and demographic data. The weight of each indicator of flood quantity formula was determined from previous research results, and it can be standard of Risk Scale from the other Country research such as cited in the above part of this paper.

III. RESULTS AND DISCUSSION

This study's five rivers are second-order rivers, where the main river or the first-order river is the Citarum River. The map used to analyze rivers in this study is developing a 1: 25,000 scale Citarum watershed map in GIS format. There are 2 study location maps; are the Citarik watershed map and 4 other watersheds that pass through the city of Cimahi in one map.

A. Rivers Map

Maps of the Citarik river and the Citarum river are shown in Fig 2, and Map of the Cimahi river, Cibeureum river, Cilember river and Cisangkan river are shown in Fig 3.

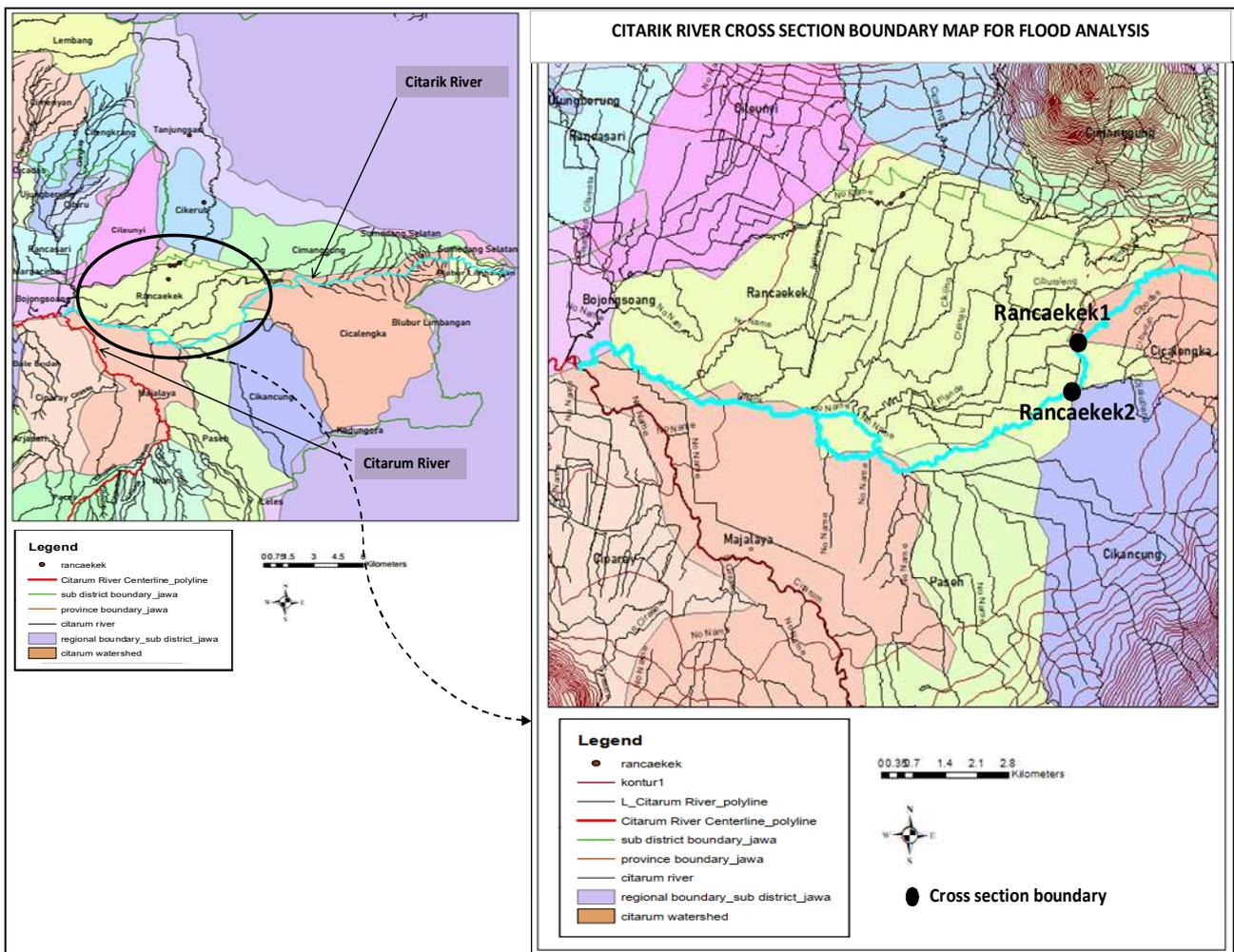


Fig. 2 Cross-section Boundary of Citarik River

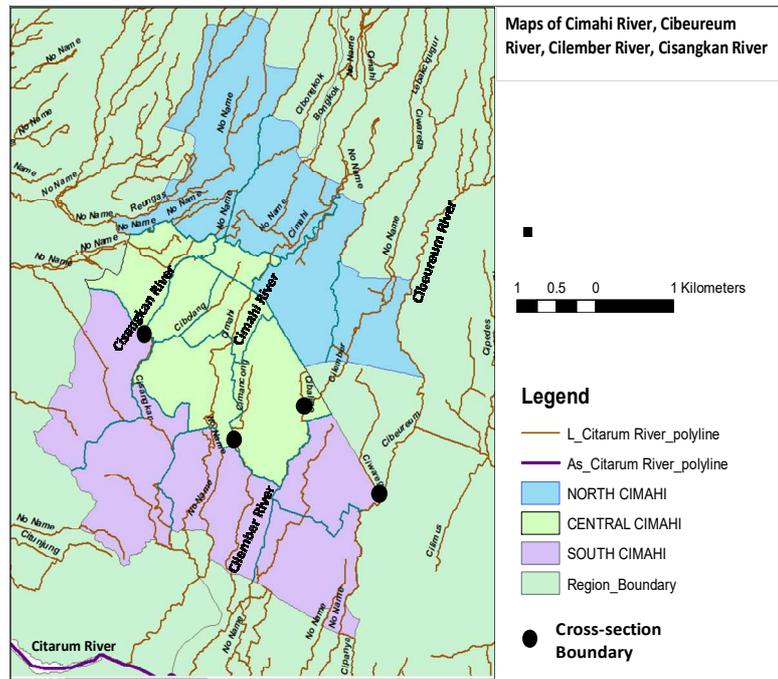


Fig. 3 Map and Cross-section Boundary of Cimahi, Cibeureum, Cilember (Cibaligo) and Cisangkan River

B. Load Discharge of Rivers in Study Area

Load discharge is obtained from the convolution method shown in Equation 2 above, while the runoff coefficient is obtained from the analysis of land use maps. Load discharge

is determined in the river cross-section boundary in upstream of the flood area. The boundary locations of all rivers are shown in Fig 2 and Fig 3.

TABLE III
LOAD DISCHARGE, CAPACITY DISCHARGE, AND % OF INUNDATION

River Parameter	Jan	Feb	Mar	Apr	Mei	June	July	Aug	Sept	Oct	Nov	Dec
Cimahi												
$Q_{\text{flood}}(\text{m}^3/\text{s})$	39.98	42.74	40.22	55.87	60.16	32.72	32.07	22.26	36.15	63.51	54.82	48.55
$Q_{\text{cap}}(\text{m}^3/\text{s})$	88.28	88.28	88.28	88.28	88.28	88.28	88.28	88.28	88.28	88.28	88.28	88.28
% of inundation	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cibeureum												
$Q_{\text{flood}}(\text{m}^3/\text{s})$	44.05	47.09	44.31	61.56	66.28	36.05	35.34	24.53	39.83	69.97	60.40	53.49
$Q_{\text{cap}}(\text{m}^3/\text{s})$	80.36	80.36	80.36	80.36	80.36	80.36	80.36	80.36	80.36	80.36	80.36	80.36
% of inundation	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cisangkan												
$Q_{\text{flood}}(\text{m}^3/\text{s})$	18.04	19.28	18.15	25.21	27.14	14.76	14.47	10.04	16.31	28.65	24.73	21.91
$Q_{\text{cap}}(\text{m}^3/\text{s})$	19.18	19.18	19.18	19.18	19.18	19.18	19.18	19.18	19.18	19.18	19.18	19.18
% of inundation	0.00	0.54	0.00	31.42	41.51	0.00	0.00	0.00	0.00	49.39	28.94	14.21
Cilember												
$Q_{\text{flood}}(\text{m}^3/\text{s})$	25.93	27.73	26.09	36.24	39.02	21.23	20.80	14.44	23.45	41.20	35.56	31.49
$Q_{\text{cap}}(\text{m}^3/\text{s})$	9.62	9.62	9.62	9.62	9.62	9.62	9.62	9.62	9.62	9.62	9.62	9.62
% of inundation	169.58	188.20	171.20	276.74	305.65	120.65	116.25	50.11	143.76	328.23	269.63	227.39
Citarik-1												
$Q_{\text{flood}}(\text{m}^3/\text{s})$	171.86	200.23	267.87	151.29	179.16	142.79	106.45	85.00	101.17	274.02	273.01	266.19
$Q_{\text{cap}}(\text{m}^3/\text{s})$	232.3	232.3	232.3	232.3	232.3	232.3	232.3	232.3	232.3	232.3	232.3	232.3
% of inundation	0.00	0.00	15.31	0.00	0.00	0.00	0.00	0.00	0.00	17.96	17.52	14.59
Citarik-2												
$Q_{\text{flood}}(\text{m}^3/\text{s})$	256.58	298.93	399.92	225.87	267.48	213.18	158.93	126.89	151.04	409.10	407.58	397.41
$Q_{\text{cap}}(\text{m}^3/\text{s})$	348.1	348.1	348.1	348.1	348.1	348.1	348.1	348.1	348.1	348.1	348.1	348.1
% of inundation	0.00	0.00	14.89	0.00	0.00	0.00	0.00	0.00	0.00	17.52	17.09	14.17

In the Citarik watershed, there are 2 cross-sections analyzed, namely Rancaekek1 and Rancaekek2. Analysis of the two cross-sections of the Citarik river aims to detect inundation areas. The area of Citarik-Rancaekek1 watershed is 70.34 km², and 20.6 km length of the main river. Based on the hydrograph it was obtained peak discharge of 4.95 m³/s and 2.39 hour of peak time. Cross-section Rancaekek1 is located at an elevation of 674.55 m MSL. The area of Citarik-Rancaekek2 watershed is 111.6 km², and 22.3 km length of the main river. Based on the hydrograph it was obtained peak discharge of 7.42 m³/s and 2.49 hours of peak time. Cross-section Rancaekek2 is located at an elevation of 667.74 m MSL.

Monthly load discharge, percentage of inundation area, and capacity discharge of rivers in the study location are shown in Table 2. Load discharge is obtained from equation 1 with 50-year return period rainfall. The cross-section's discharge capacity on the boundary cross-section is determined based on the existing river cross-section geometry obtained from field measurements. For the cross-section of the Cilember river in the Central Cigugur region, the existing cross-sectional area is used. This cross-section is very small due to the narrowing of the river border and river bed aggradation so that it is planned to be normalized in 2020.

According to Table 2, no floods were overflowing the Cimahi river and Cibereum river. The Cisangkan River overflows its maximum in October with an inundation area of 49.39% of the watershed area. The heaviest flood occurred in the Cilember river, where flooding still occurs at the lowest rainfall. The maximum flood occurred in October with an inundation area of 329.23% of the watershed area. The Citarik River in the Rancaekek1 section had a maximum flood in October with a percentage of inundation area of 17.96% of the watershed area, while in the Rancaekek2 section, the maximum flood occurred in October with a percentage of inundation area of 17.52% of the watershed area.

The maximum inundation height and depth were obtained from an unsteady one-dimension model, local disaster agency data, field observations and interviews with residents of 5 flood-affected villages in the inundation area.

The depth of the inundation results of one-dimensional modeling can only analyze the flow in the river. The field flow must be analyzed with a two-dimensional flow that requires a detailed topographic map for distributed analysis as input to each grid. Based on this case, the land flow patterns are combined with information from residents in the flood area at 10 inundation points in each village. This data is also matched with data from the regional disaster management agency in Bandung District and Cimahi.

C. River Flood Quantity and Risk Scale

Flood quantification results and risk scale for all rivers based on Equation 4 are shown in Table 4. The highest flood quantity is the Cilember river flood with $K_f = 16.18$ and 5 risk scale. The second-largest flood is the Citarik-Rancaekek2 river, which is flooding in the downstream area of the Citarik river.

TABLE IIIV
FLOOD QUANTITY AND RISK SCALE FOR ALL RIVERS

Name of River	A_i	A_{ac}	D (hour)	H (m)	Flood Quantity K_f	Risk Scale
Cimahi	0	0	0	0	0	No Flood
Cibereum	0	0	0	0	0	No Flood
Cilember	329.2	90	18	3	16.18	5
Cisangkan	49.39	90	5	0.5	4.43	3
Citarik-1	17.96	80	6	1	3.64	2
Citarik-2	17.52	80	18	1.5	6.18	4

The lowest flood is on the Citarik-Ranca1 river, which is the Citarik river area in the upstream Rancaekek District. Floods in this region are low because the water flows to Rancaekek2 area so that this region has a higher quantity of flooding.

The Cilember river flood, with a risk scale of 5, is indeed a case of severe flooding. The conditions are densely populated, narrowing the river border, riverbed aggradation, high landfill in the downstream, and a wall toll road. A river area's central and downstream region is generally a flood-prone area if no integrated management integrates between river areas and regional urban areas. This happens because the central part of a river area will increase river discharge due to changes in land cover in the upstream area. The impact will increase if the downstream flow is hampered due to development faster in the upstream and without spatial planning, which refers to the predetermined regional layout plan. Flood area of the Cilember river is the lowest part of this river located in Cimahi, so this part of the puddle is also the boundary of Cimahi and District of Bandung; therefore, good coordination is needed.

Flood category and level of damage of each river in this study are shown in Table 5.

TABLE V
FLOOD CATEGORY AND LEVEL OF DAMAGE

Name of River	K_f	Quantity of Risk	Category	Level of Damage
Cimahi	0	0	No Flood	Secure
Cibereum	0	0	No Flood	Secure
Cilember	16.18	5	Very High	Very High Damage
Cisangkan	4.43	3	Medium	Damage
Citarik-1	3.64	3	low	Low Damage
Citarik-2	6.18	4	High	High Damage

Cimahi river and Cibereum river, based on the results of this study, are safe from flooding. These two rivers are the largest river in the city of Cimahi. Cimahi River, although there is a narrowing of the river border in several cross-sections, can still accommodate runoff loads in its watershed area. Bandung borders Cibereum River in the east, and in the west is adjacent to the Cilember river. From the results of field observations, there was an engineering diversion of the Cibereum river flow to the Cilember river so that most of the discharge of the Cibereum river was accommodated by the Cilember river.

IV. CONCLUSION

Flood quantification is a tool to quantitatively measure all flood events starting from the inundation area's physical condition, inundation characteristics, and the level of damage caused. All rivers' flood quantity and the risk scale in this research are dominated by a percentage indicator of the inundation area's activity area. This result shows that the flood has caused significant losses both financially and emotionally.

ACKNOWLEDGMENT

This research is fully supported by Ristekdikti Competitive Research, 7/E/KPT/2019, and UNJANI Competitive Research SKEP/133/UNJANI/V/2019. The authors fully acknowledged The Ministry of Research Technology Higher Education (Ristekdikti) and Jenderal Achmad Yani University for the approved fund, making this critical research viable and effective.

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