Flood Analysis and Estimating Economic Losses in an Affected Area (Case Study: Cikapundung Watershed)

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Source: Air, Soil and Water Research, 15(1)

Published By: SAGE Publishing

URL: https://doi.org/10.1177/11786221221131277

Flood Analysis and Estimating Economic Losses in an Affected Area (Case Study: Cikapundung Watershed)

Air, Soil and Water Research
Volume 15: 1–10

DOI: 10.1177/11786221221131277

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ABSTRACT: The Cikapundung Watershed is part of the Citarum watershed, which functions as the main drainage of the center of Bandung City. High exploitation of space and water resources can trigger flooding, as is often the case in the Cikapundung watershed. Flooding can be caused by rapid population growth, land degradation, and climate change. In this study, four types of methods were used to analyze rainfall frequency, and the type III Log Pearson distribution method was found to meet the requirements for use. A match test was carried out using the chi-squared method and the Smirnov-Kolmogorov method. Hydraulics analysis was carried out by the HEC-RAS method with different return periods to calculate the depth of flooding. HEC-RAS was used because it is considered highly compatible and relevant to geatographic information systems. The return periods modeled with HEC-RAS were 2, 5, 10, 25, 50, and 100 years. Based on the calculation results, the Cikapundung watershed runoff coefficient in 2020 was .43. The increased return period suggests that the area of flood inundation is becoming wider. The downstream impacts of wider flood inundation include all sectors that are more affected by flooding. This causes losses to increase as the flood payback period increases. The total estimated loss for the 25 return periods of flood events in the Cikapundung watershed is around 1,124 million rupiah, and the affected population is around 700,000 people.

KEYWORDS: Flood risk, Hecras, estimated loss, watershed

RECEIVED: June 11, 2022. **ACCEPTED:** September 21, 2022.

TYPE: Original Research

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Introduction

The Cikapundung watershed is part of the Citarum watershed, and the Cikapundung River is its main river. The headwaters of the river are located in the Lembang District, West Bandung Regency. The water flows south and empties into the Citarum River. The Cikapundung River is one of the rivers that is vital to the area of West Bandung Regency, Bandung Regency, and Bandung City. In addition, the Cikapundung River has an ecological function in the Bandung Basin. The Cikapundung River is located in the upper reaches of the Citarum watershed and has an important role in the development of the city through which it passes. Furthermore, it is one of the largest water suppliers to the Citarum River. The Cikapundung River functions as a source of raw water and as the main drainage channel of the city of Bandung (Bachrein, 2012; Maria, 2008; Maria & Lestiana, 2014; Murran & Suciyani, 2021; Pratami, 2015; Solihin & Putri, 2020; Wardhani & Salsabila, 2022). The Cikapundung watershed has a catchment area of 14,211 ha, and the river crosses the city of Bandung along 15.5 km of its length. The altitude of the river is 650 to 2,067 m above sea level with an upstream slope of 3% to 10% and downstream slope of 0% to 3%. In the Cikapundung watershed area, there space and water are exploited due to the rapid population growth, and 10.57 km of the length of the river (68.20%) is a densely populated residential area filled with buildings (Bachrein, 2012; Murran & Suciyani, 2021). The rapid growth of the population has led to a high need for land for housing, which results in changes in land function (Dewanti, 2017).

Land use change in the upper reaches of the Cikapundung sub-watershed located in Lembang District is reducing the ability of the land to absorb water (Nurrochman, 2018). Land in the central urban area has been changed to many cultivation areas to support the sustainable development of the city area. Residential areas have been set aside and are located in the border areas of cities and river. Land use at the river border causes river silting, which results in reduced function of the river as a reservoir of rainwater (Murran & Suciyani, 2021).

Changes in land cover affect the overall hydrological pattern of the watershed (Salim et al., 2019). The exploitation and utilization of watersheds increases the risk of major flooding. Flooding indicates an imbalance of the environmental system in the process of drying surface water and is affected by the magnitude of the water discharge that exceeds the capacity of the jetting area (Suripin, 2004). Hydrometeorological disasters such as floods cannot be avoided completely but can be managed by reducing risks and establishing effective prevention strategies using geospatial tools and other carrying capacity systems (Jha & Afreen, 2020).

Flooding is a disaster that has had a great impact in various countries. Floods have environmental, social, and economic impacts (Bachri et al., 2021). To minimize the impact of this disaster, hydrological models are used for flood forecasting (Tamiru & Dinka, 2021). If there is no handling of land-use planning governance, the maximum increase in discharge will occur every year (Thoummalangsy et al., 2019).

Flood assessment consists of four main steps: hydrological frequency analysis, hazard assessment, exposure analysis, and economic loss estimation. Flood frequency analysis is one of the important aspects of hydrology for estimating future events, as well as providing an assessment of flood risk (Thoummalangsy et al., 2019). Indicators of flood hazard generally include area, water depth, flow velocity, and duration. The area and depth of the flood are categorized into three classes: low, medium, and high. These parameters are associated with economic losses and other vulnerability assessments. Damage assessment can estimate the cost of compensation for an exposed area and the recovery of the affected area (Jha & Afreen, 2020; Thoummalangsy et al., 2019). Economic loss assessment aims at disaster management and other planning, such as disaster risk insurance for certain buildings. Jayantara (2020) carried out a calculation of economic losses using the method of the Economic Commission for Latin America and the Caribbean (ECLAC) as a basis and analysis of geographic information systems to identify flood-affected areas in Bandung Regency. The ECLAC method can identify damage to each component of a building and estimate losses caused by floods, making it easier for the government to prepare budgets and handle rehabilitation and reconstruction. This method comprehensively calculates damage and losses and is carried out in each sector (Putra et al., 2020; Wardhono & Rondhi, 2010).

The main parameter in hydraulic modeling for the assessment of flood hazards is water discharge. Prediction of flood hazards usually uses a flood inundation map that can be digitally modeled by assessing the difference in water surface elevation by measuring data on flood zones in situ (Mokhtar et al., 2018). HEC-RAS is one of the most widely used software in analyzing channel flows and flood inundation. HEC-RAS can simulate the profile of the water surface for varying stable flow and specific levels of flood inundation (Khattak et al., 2015). Many studies have used HEC-RAS software to model floods, such as modeling flood inundation maps based on discharges in the Padang Terap River, Malaysia (Mokhtar et al., 2018), simulating water surface profiles and determining the extent of flood inundation in the Kabul River in Pakistan (Khattak et al., 2015), flood modeling in Godavari River, India (Kute et al., 2014), modeling runoff results from an Artificial Neural Network (ANN) hydrological model downstream of the Baro Akobo River watershed, Ethiopia (Tamiru & Dinka, 2021), and simulating the profile of flood water levels and flood inundation in Sekanak Subsystem, Palembang (Al Amin et al., 2018).

This study discusses the land use and land-cover changes that have occurred around the banks of the Cikapundung watershed in terms of vegetation and open/bare substrate. To describe the hydrological phenomena, this study models the discharge of extremities in the Cikapundung watershed area. The data obtained can be used to determine the extent of the flooding that has occurred. To identify a model that resembles the actual cross section of the Cikapundung River, an existing cross-section was analyzed using HEC-RAS 5.0.7 software. The parameters were then analyzed for associations with economic loss assessment based on the extent and depth of flood inundation.

Flood modeling was carried out to determine the impact of floods with different return periods of 2, 5, 10, 25, 50, and 100 years. Based on the modeling results, the impact of the flood on the population sector, building sector, road sector, and agricultural sector can be analyzed. After that, we can calculate the estimated economic loss in each flooded sub-district.

Data and Methods

Several types of data are used in this study, including rainfall data and elevation data, as shown in Table 1. This research was conducted in the Cikapundung watershed, which can be seen in Figure 1. The area in the Cikapundung watershed consists of 20 sub-districts, all of which were modeled using HEC-RAS to see the impact of floods in each sub-district.

This research has four main objectives: the analysis of (1) hydrological conditions, (2) land cover conversion, (3) potential flood profiles, and (4) estimated economic losses in the affected area. The study area encompasses the Cikapundung watershed from upstream to downstream. The hydrological analysis was divided into rainfall analysis and debit modeling analysis.

Data from rainfall observation and coordinate stations were used to produce a rainfall map. The regional rainfall was calculated using the Thiessen Polygon method. This study used four methods for analyzing the frequency of rainfall: log-normal, log-Pearson type III, and Gumbel distributions. The design rainfall was calculated for return periods of 2, 5, 10, 25, 50, and 100 years. The statistical parameters for rainfall data must be considered in terms of selecting the appropriate distribution for the distribution of the data. The chi-squared and the Smirnov-Kolmogorov methods were used to test for fit.

The Nakayasu Synthetic Unit Hydrograph (HSS) method was used to analyze the discharge design. This method does not use rainfall or part of the total rain that produces direct runoff. The equation in the Nakayasu HSS method only uses two watershed parameters (watershed area and the length of the main river) and then only uses main data development. The total discharge used in the calculation is the total of runoff discharge (HSS Nakayasu) and base flow (half of peak discharge value).

This study used a two-dimensional HEC-RAS 5.07 model to analyze the potential for flooding that can occur in the Cikapundung watershed. Hydraulic parameters are required by the HEC-RAS program, including the cross section of the river (width and depth), the Manning coefficient (n), and the flow rate. The condition used was unsteady flow. The basic equation for river flow is based on a physical process and the laws of mass and momentum conservation. The physical process that occurs is described using a mathematical equation such as the Saint Venant equation.

The topographic data used in the flood modeling analysis in HEC-RAS is from the Indonesia Digital Elevation Model (DEMNAS). DEMNAS data are built by adding mass point data resulting from stereo-plotting from several data sources, such as IFSAR (5-m resolution), TERRASAR-X (5-m resolution), and ALOS PALSAR (11.25-m resolution). In the

Table 1. Types of Data in Research.

NO.	DATA	YEAR	APPLICATION			DATA SOURCE
			HYDROLOGICAL ANALYSIS	HYDRAULIC ANALYSIS	SPATIAL ANALYSIS	
1.	Rainfall	2010–2019	✓			Directorate of engineering affairs for water resources, ministry of public works
2.	*Data Elevation Model (DEM)*	2018		✓		DEMNAS, geospatial information agency
3.	Administration maps	2020		✓	✓	River basin headquarters agencies, BBWS CITARUM
4.	Landcover map	2011–2020	✓		✓	Ministry of environments and forestry of the Republic of Indonesia
5.	*OpenStreetMap*	2021	•	•	✓	https://www.openstreetmap.org/

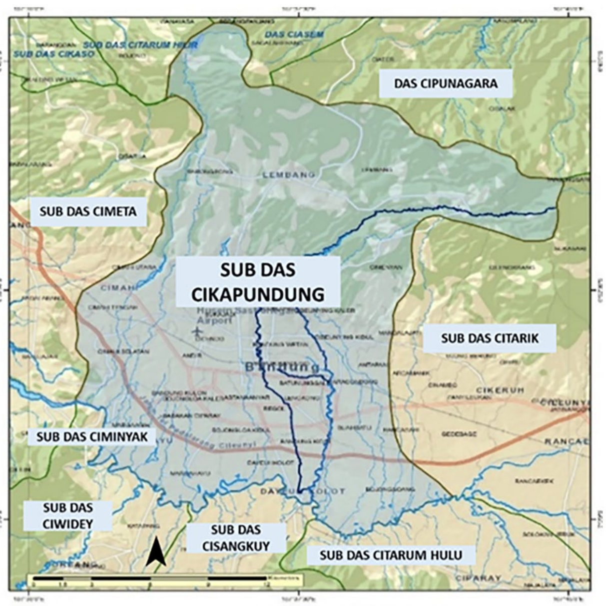

Figure 1. Map of study location.

Table 2. Replacement Unit Value.

SECTOR	REPLACEMENT UNIT VALUE (IDR)
Agriculture	9,295,500 ha
Main road	1,480,000 m
Local road	740,000 m

two-dimensional model, the cross-sectional data do not need to be presented manually like in an analysis with a one-dimensional model. The two-dimensional model only defines the mesh on the terrain where the flow direction is determined based on 2D hydraulic computations and terrain representation. Next is the determination of "breaklines" on the left and right sides of the river. The determination of breaklines is done to control the direction of flow and ensure that the water flow is blocked by the elevation of the embankment along the breaklines themselves.

When carrying out flood modeling, the upstream and downstream sections must be ensured to have boundary condition lines. Boundary conditions upstream are defined as the initial conditions for the flow of water, and downstream, they are defined as the area where the flow flows. By looking at the characteristics of the Cikapundung River, which tends to be straight and not too winding, this study determined a Manning coefficient of .025. The boundary conditions in this study are the changes in flow rate at the upstream boundary and constant water level at the downstream boundary. The flow rate entered is the designed flood discharge obtained from the calculation results of the Nakayasu method with return periods of 2, 5, 10, 25, 50, and 100 years.

Spatial analysis was used to identify the total area affected by flooding in various sectors, including population, housing, road, and agriculture sectors. The estimated economic losses were calculated using the method of the Economic Commission for Latin America and the Caribbean (ECLAC). The ECLAC method is used to determine the amount of damage caused by various types of disasters, especially floods, in terms of damage, loss, and economic impact.

The ECLAC method can be calculated using equation (1).

$$Loss = \left(Number\ of\ Affected\ Area\right) \times \left(Unit\ Value\right) \times \left(Damage\ Factor\right) \quad (1)$$

The replacement unit value is determined based on the unit loss value data per sector obtained through data from Upper Citarum Basin Flood Management (UCBFM) in 2010. The replacement unit value based on the type of sector can be seen in Table 2. The damage factor based on the function of losses due to flooding is obtained based on data compiled by the Japan International Cooperation Agency (JICA, 2007). The flood loss function can be seen in Figure 2.

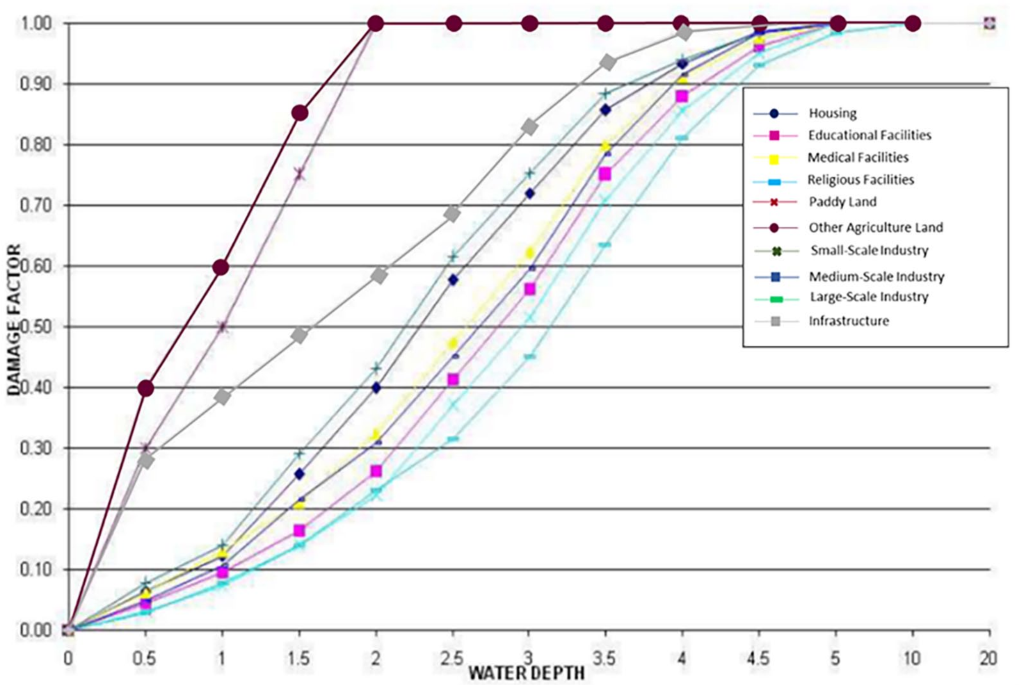

Figure 2. Flood loss function.

Results and Discussion

Regional rainfall analysis

Regional rainfall analysis was carried out using the Thiessen Polygon method, as shown in Figure 3. This method considers the weight score of each station, which represents the area around it. The impact on each rain station in the Cikapundung watershed can is presented in Table 3.

Based on the calculation results, the Dago Pakar-Bengkok rain station has the most coverage, with a total area of 208.08 km² (51.89% of the total area of the entire watershed). Regional rainfall in the Cikapundung watershed is 2,514 mm/year. This is due to the distance between rain stations, which are quite close in the northern and eastern parts of the watershed. Thus, the Dago Pakar-Bengkok rain station represents rainfall data from the central part of the Cikapundung watershed to its southern part.

Rainfall frequency analysis

The average maximum daily rainfall determined using the Thiessen Polygon method enables prediction of its recurrence probability. This study used four methods to analyze the frequency of rain, namely the Gumbel, normal, log-normal, and log-Pearson type III distribution methods. The designed rainfall was estimated based on an analysis of the probability distribution of rainfall by measuring the dispersion, followed by measuring the dispersion with logarithms, and then testing the suitability of the distribution.

Frequency analysis of the normal and Gumbel methods generated a standard deviation of 24.07. The coefficient of variance was .33, the coefficient of deviation was .87, and the coefficient of kurtosis was 2.49. The log-normal and log-Pearson type III methods had a standard deviation of 0.1, coefficient of variance of .07, coefficient of sloping of .65, and coefficient of kurtosis of 2.25. The coefficient values are presented in Table 4. Based on the data in Table 4, only the log-Pearson type III distribution fulfilled the requirements for use.

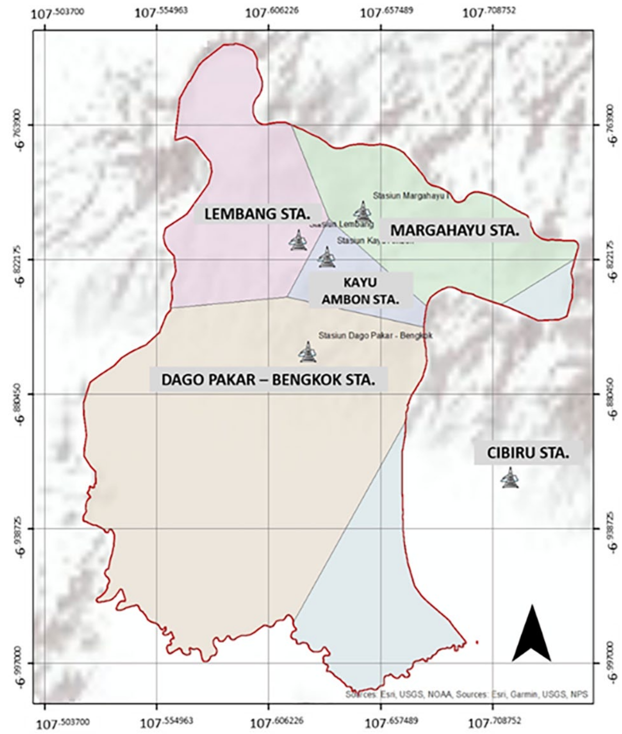

Figure 3. Average maximum daily rainfall of Cikapundung watershed.

Table 3. Total Rainfall Area for Each Rainfall Station.

STATION	TOTAL AREA (KM^2)	PERCENTAGE (%)
Cibiru	52.22	13.02
Dago Pakar Bengkok	208.08	51.89
Kayu Ambon	17.21	4.29
Lembang	65.71	16.39
Margahayu I	57.79	14.41
Total area	401.02	100

Therefore, all following rainfall estimations were calculated with this distribution method.

Calculation of rainfall design of selected distribution method

The design rainfall calculations for each return period derived using the log-Pearson type III distribution method can be seen in Table 5.

Goodness of fit test

The goodness of fit test was employed to determine the most appropriate distribution frequency method from the sample data to the probability distribution function, which is estimated to represent the statistical distribution of the analyzed sample. The chi-squared and Smirnov-Kolmogorov methods were used to assess the applicability of the parameters.

To determine the acceptability of the distribution method, the calculated X^2 value was compared with the critical X^2 value. X^2 was calculated as 1, while the critical X^2 value was 5,991 for 10 data, $\alpha = .05$, and DK = 2. Based on this comparison, the log-Pearson type III distribution method meets the requirements of the chi-squared test.

For $\alpha = .05$ and $n = 10$, the critical value of ΔP was 0.41. The actual value of ΔP was calculated as 0.15. Based on this calculation, the calculated ΔP from the log-Pearson type III distribution method was smaller than the critical ΔP value. Therefore, for the calculation of design rainfall, this study used the log-Pearson type III distribution method for the following discharge design processing step.

Cikapundung watershed runoff coefficient

Figure 4 shows the land use in the Cikapundung watershed in 2020. It can be seen that the land use is dominated by residential areas at 210,381 km^2. Based on the results of the multiplication between the runoff coefficient and the area of each land use, the runoff coefficient for the entire Cikapundung watershed for 2020 was obtained as .4. This means that 40% of the rainwater within the research area will become surface runoff, while 60% will infiltrate into the ground (Nganro et al., 2018).

Table 4. Utilization Requirements of Different Distribution Types.

DISTRIBUTION TYPE	REQUIREMENTS	RESULTS	DESCRIPTION
Gumbel	$C_k \leqslant 5.4002$	$C_k = 11.56$	Not accepted
	$C_s \leqslant 1.139$	$C_s = 2.21$	Not accepted
Normal	$C_k \approx 3$	$C_k = 11.56$	Not accepted
	$C_s \approx 0$	$C_s = 2.21$	Not accepted
Log-normal	$C_s \approx 3C_v + C_v{}^2 = 3$	Cs = 1.65	Not accepted
	$C_k \approx 5.383$	$C_v = 0.07$	Not accepted
Log-person type III	$C_s \neq 0$	$C_s = 1.65$	Accepted
		$C_v = 0.07$	Accepted

At the time when this research was conducted, the maximum rainfall data available from the Indonesia Ministry of Public Works and Housing was 2019 data. The land use data used to determine the runoff coefficient was available until 2020. The runoff coefficient analysis was carried out based on data obtained from land use data from the Indonesia Ministry of Environment and Forestry for 2011 to 2020. Land use data in the last 10 years was used so that the results of the analysis can describe the present physical condition of the Cikapundung watershed.

Rainfall design distribution

Before calculating the design flood hydrograph, it is necessary to have an hourly rainfall distribution at certain time intervals. In general, the shape of the hydrograph unit is determined by the rainfall over a certain period. Therefore, previously obtained daily rainfall data can be broken down into rainfall components according to the rain duration unit in the theory used, namely hourly rainfall. This study used the distribution of precipitation for 6 hours as one of the essential data points in generating the design flood hydrograph. The calculation results for the hourly rainfall ratio are summarized in Table 6.

Design flood discharge according to the Nakayasu HSS method

According to the Nakayasu HSS method, the design flood discharge indicates that the increase in the return period will be directly proportional to the design discharge value. In other words, the bigger the return period scenario is, the higher the design discharge will be. A comparison of debit values from each return period is represented in Figure 5.

Potential flood profiles

Figure 6a to 6f show the results of the analysis of the two-dimensional flood profiles model using HEC-RAS 5.07 in the

Table 5. Return Period Rainfall in Cikapundung Watershed According to Log-Pearson Type III Distribution.

NO.	RETURN PERIOD	$\overline{LogX}$	K_T	S LOG	LOG X_{TR}	X_T
1	2	1.937	−0.180	0.128	1.914	82.126
2	5	1.937	0.745	0.128	2.033	107.828
3	10	1.937	1.341	0.128	2.109	128.506
4	25	1.937	2.066	0.128	2.202	159.076
5	50	1.937	2.585	0.128	2.268	185.332
6	100	1.937	3.087	0.128	2.332	214.845

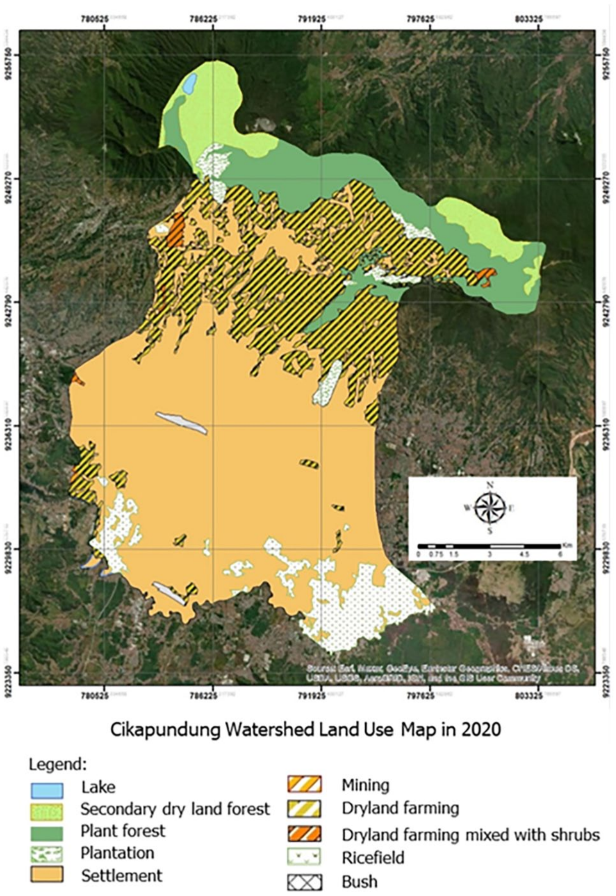

Figure 4. Land use of Cikapundung watershed.

Cikapundung watershed in the return periods of 2, 5, 10, 25, 50, and 100 years. Based on the results of HEC-RAS modeling for a 2-year return period (Figure 6a), the areas that have the largest inundation area are the Batununggal and Lembang Districts at 1.69 and 1.268 km^2. The smallest area in the 2-year return period flood is in Cicendo District, covering an area of 0.022 km^2. The results of the 5-year return period flood modeling (Figure 6b) show that the areas with the most flood inundation are the Batununggal District and Buahbatu District, covering areas of 1.903 and 1.542 km^2. The area with the smallest flood inundation in the 5-year return period is Bajongloa Kidul District, covering an area of 0.00 km^2. The areas with the most flood inundation in the 0-year return period in Figure 6c are Buahbatu District and Batununggal District, covering areas of 2.106 and 1.978 km^2, and the smallest area of flood inundation in this period is Cilengkrang District with an area of 0.027 km^2.

Figure 6d shows the results of flood modeling with HEC-RAS for a 25-year return period. Based on the results of this modeling, the areas with the most flood inundation are Buahbatu District and Batununggal District, covering areas of 3.628 and 2.241 km^2. The area with the least flood inundation in this period is Cilengkrang District at 0.027 km^2. Flood modeling in the 50-year return period can be seen in Figure 6e. The largest areas of flood inundation are Buahbatu District, covering an area of 3.987 km^2, and Batununggal District, covering an area of 2.295 km^2. The area with the smallest flood inundation in this period is Cilengkrang District, covering an area of 0.026 km^2.

For a 100-year return period, flood modeling can be seen in Figure 6f. Based on the modeling results, the areas with the largest flood inundation in this period were Buahbatu District, covering an area of 4.835 km^2, and Lengkong District, covering an area of 2.627 km^2. The area with the smallest flood inundation in this period was Cilengkrang District with an inundation area of 0.026 km^2.

Estimated losses according to sector

This study compared the economic losses in each sector (population, housing, roads, and agriculture). Almost all calculation results are presented as histograms so that the trend in each return period can be seen for each sub-district. The units of measurement are the estimated loss values in rupiah for each affected sector. The comparison of estimated losses in each return period is shown in Figures 7 to 10.

The graphs in Figures 7 to 10 indicate that with the increase in the return period scenario of flood predictions, the estimated loss results also increase. As the return period increases, the results of the flood inundation become wider. Wider flood inundation increased in all sectors more affected by flooding.

Table 6. Distribution of Rainfall Design in the Cikapundung Watershed.

RETURN PERIOD (T_R)	(YEARS)	2	5	10	25	50	100
R DESIGN	(MM)	86.595	110.886	126.219	143.25	158.328	171.93
RUNOFF COEFFICIENT (*C*)		0.4	0.4	0.4	0.4	0.4	0.4
R_N	(MM)	34.638	44.354	50.488	57.3	63.331	68.772
HOURS	RATIO (%)						
1	0.55	19.051	24.395	27.768	31.515	34.832	37.825
2	0.35	12.019	15.391	17.519	19.883	21.976	23.864
3	0.27	9.179	11.754	13.379	15.184	16.783	18.225
4	0.22	7.551	9.669	11.006	12.491	13.806	14.992
5	0.19	6.512	8.339	9.492	10.772	11.906	12.929
6	0.17	5.785	7.407	8.431	9.569	10.576	11.485

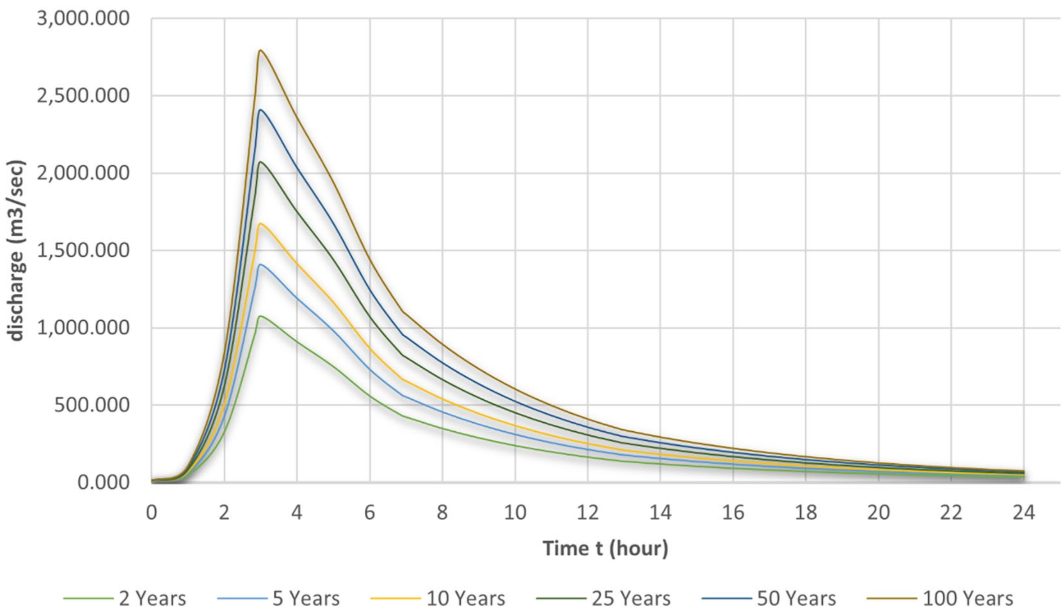

Figure 5. Comparison of flood discharge from the Nakayasu HSS design.

The impact of exposure on the population, housing, infrastructure, and agricultural sectors shows the same pattern.

Based on the results of the calculations in Figures 7 to 9, it can also be seen that Buahbatu Regency is the sub-district with the highest affected population. The sub-district that has the biggest loss in the affected building sector is Batununggal Regency. In the context of agriculture, Cimenyan Regency is the sub-district that. This causes losses to increase as the flood return period increases. The estimated total losses for each return period can be seen in Table 7.

Conclusion

The Cikapundung watershed is one of the strategic watersheds in the territory of Indonesia, especially West Java, and has the challenges of increasing flood events from year to year. Based on this research, it can be seen that regional rainfall and land use are the main factors for flood events. Regional rainfall in the Cikapundung watershed was 2,514 mm/year, and modeling results of the design flood discharge using the Nakayasu HSS method showed that the increase of return period was directly proportional to the discharge value of the flood. This study also found the economic losses in each sector (population, housing, roads, and agriculture) in each return period of a flood event. The total estimated loss for the 25-year return period of a flood event in Cikapundung watershed was about 1,124 million rupiah, and the affected population was around 700,000 people. The magnitude of the resulting loss shows that adaptation and mitigation of flood events should be priority actions for relevant stakeholders.

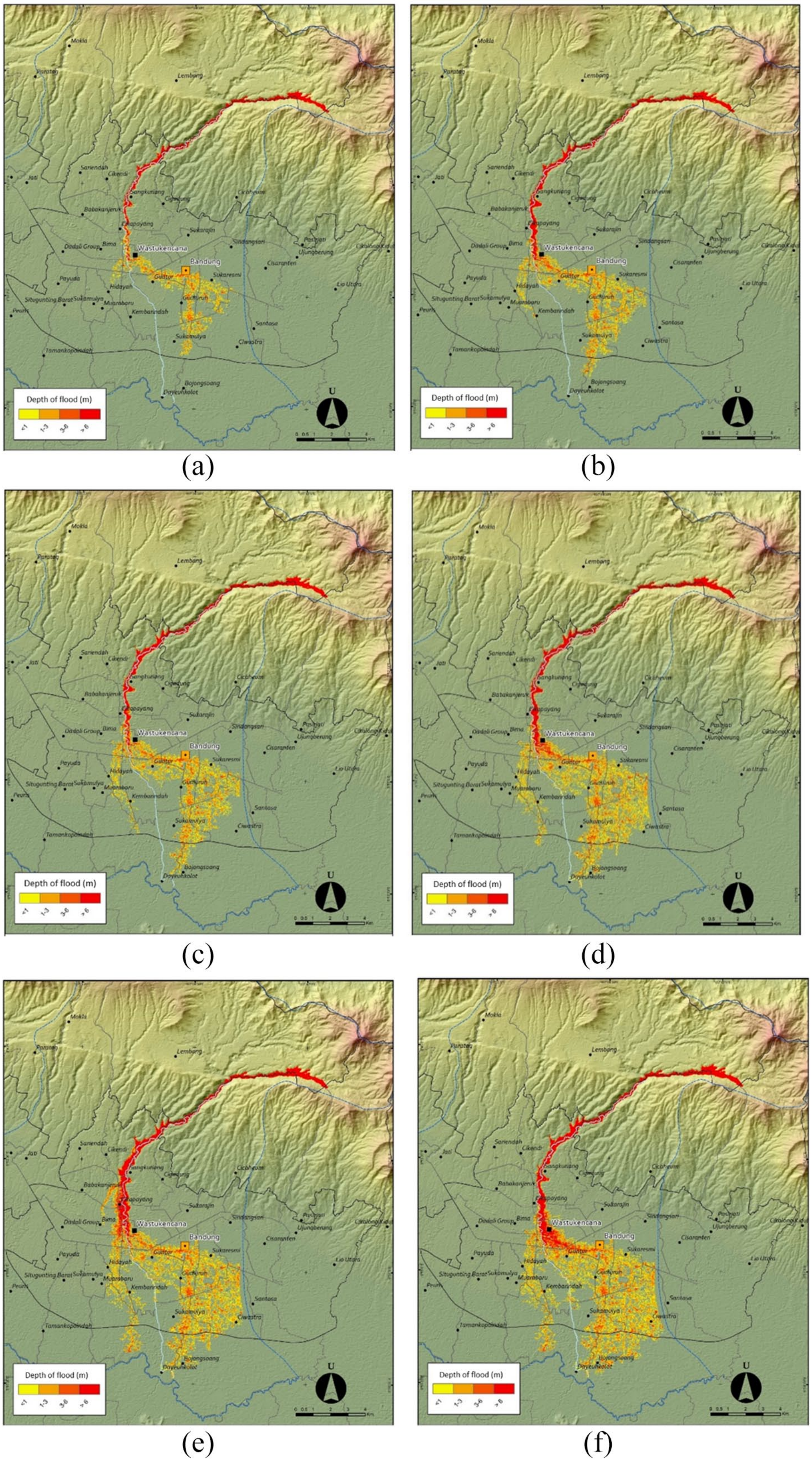

Figure 6. Model of 2-year return period flooding (a), model of 5-year return period flooding (b), model of 10-year return period flooding (c), model of 25-year return period flooding (d), model of 50-year return period flooding (e), and model of 100-year return period flooding (f).

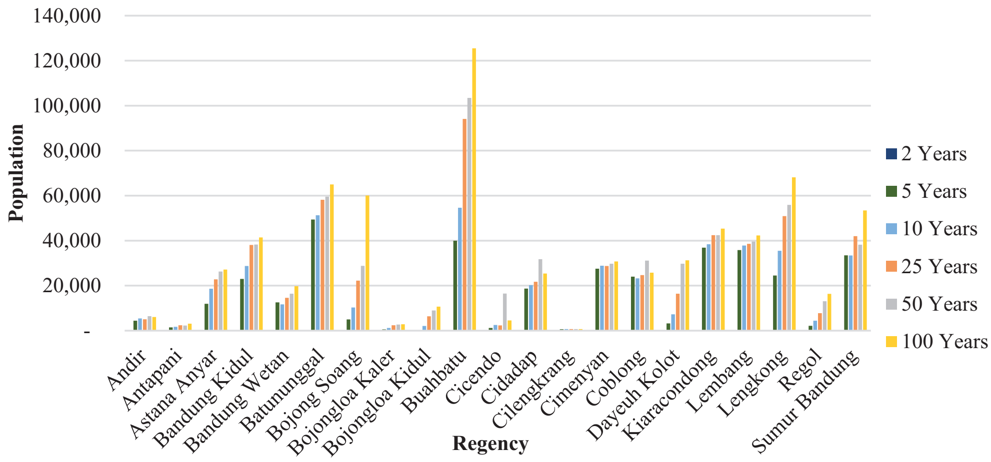

Figure 7. Total population affected according to regency.

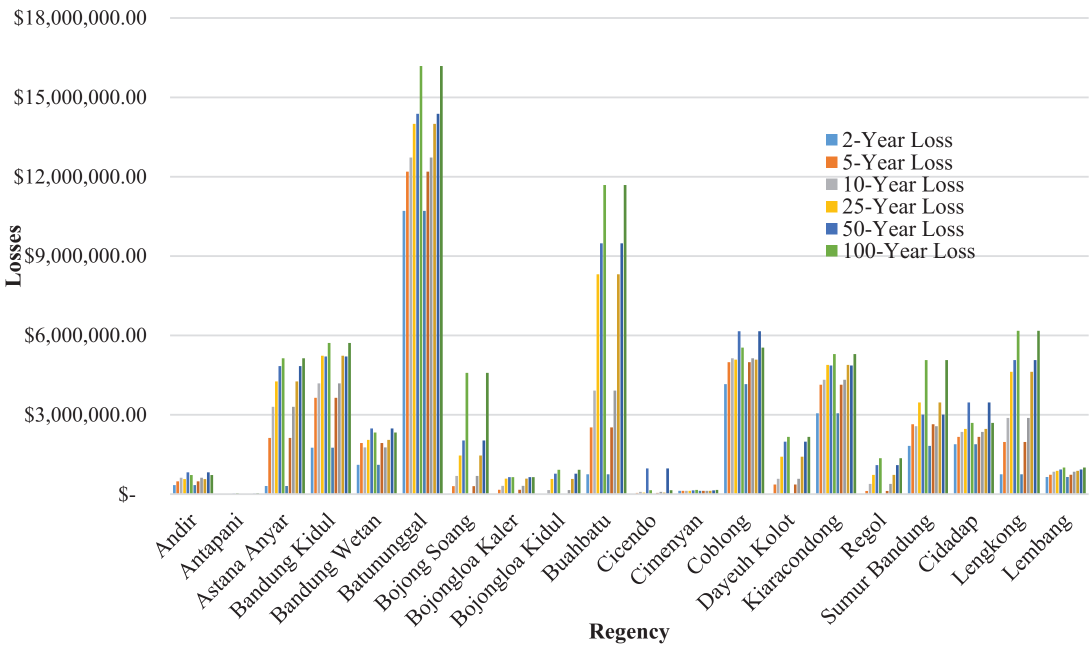

Figure 8. Total losses in the housing sector by regency.

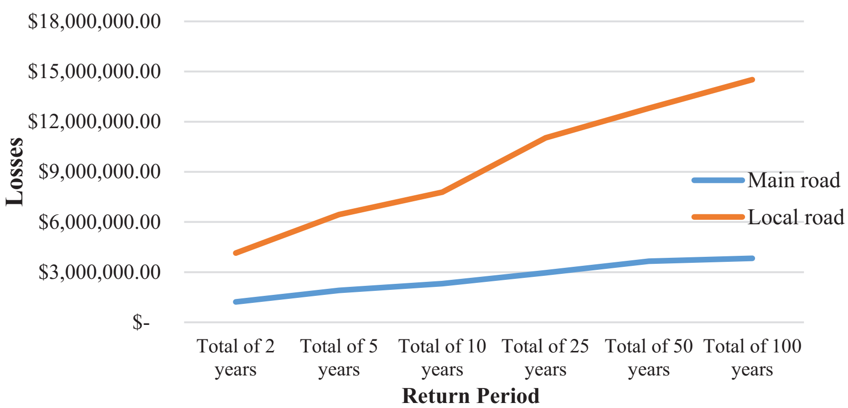

Figure 9. Total loss in road infrastructure.

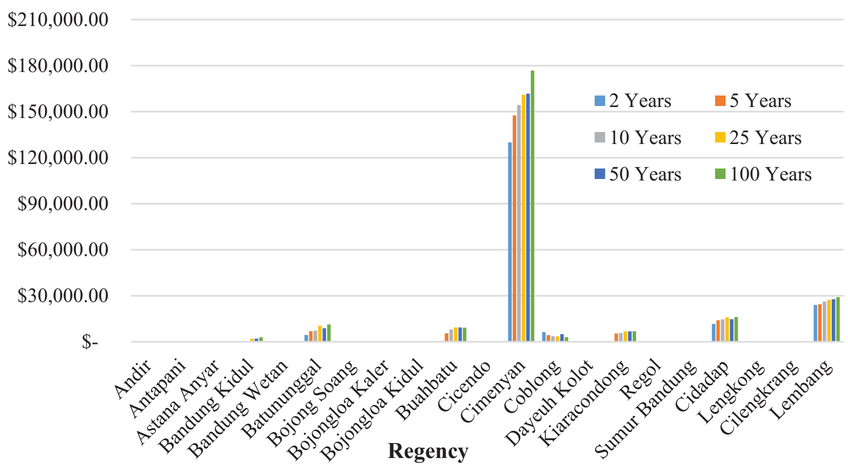

Figure 10. Recapitulation of estimated losses in the agricultural sector.

Table 7. Total Estimated Loss in Each Return Period.

RETURN PERIOD (YEARS)	TOTAL ESTIMATED LOSS	AFFECTED POPULATION
2	$32.818.917,77	238,251
5	$49.243.926,66	356,651
10	$57.286.710,28	418,196
25	$75.038.650,25	542,609
50	$85.988.676,23	622,092
100	$96.180.391,70	705,736

Author Contributions

Study conception and design: MM, SP. Data collection: SP. Analysis and interpretation of results: MM, SP, SN. Draft manuscript preparation: SP, SN. All authors contributed to the interpretation of the results and the writing of the manuscript.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This research was funded by P2MI ITB Year 2022.

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