International Journal on Advanced Science Engineering Information Technology

Vol.14 (2024) No. 1
ISSN: 2088-5334

Economic Loss due to the Failure of a Cascade Dam: A Study Case in the Saguling-Cirata-Jatiluhur Dam

Mohammad Bagus Adityawan [a,b,*], Bagus Pramono Yakti [a], Calvin Sandi [c], Andhika Wicaksono Sasongko [c], Mohammad Farid [a,d], Dhemi Harlan [c], Arno Adi Kuntoro [a], Widyaningtias [a], Edi Riawan [e]

[a] *Center for Water Resources Development, Faculty of Civil and Environmental Engineering, Institut Teknologi Bandung, Bandung, West Java, 40132, Indonesia*
[b] *Undergraduate School of Water Resources Engineering and Management, Faculty of Civil and Environmental Engineering, Institut Teknologi Bandung, Bandung, West Java, 40132, Indonesia*
[c] *Graduate School of Water Resources Management, Faculty of Civil and Environmental Engineering, Institut Teknologi Bandung, Bandung, West Java, 40132, Indonesia*
[d] *Center for Coastal and Marine Development, Faculty of Civil and Environmental Engineering, Institut Teknologi Bandung, West Java, 40132, Indonesia*
[e] *Atmospheric Sciences Research Group, Department of Meteorology, Faculty of Earth Science and Technology, Institut Teknologi Bandung, Bandung, West Java, 40132, Indonesia*

Corresponding author: [*]mbagusadityawan@gmail.com

***Abstract*— A dam break event can cause heavy loss in the affected area due to the lack of a mitigation system. Therefore, modeling the possibility of a dam break occurrence requires a risk analysis. The Saguling Dam, Cirata Dam, and Jatiluhur Dam make a cascade dam and is one of the country's most valuable assets. This study simulates a flood induced by the failure of this cascade dam. The dam break is simulated using HEC-HMS 4.6 with several dam-break scenarios due to overtopping and piping. The scenario with the highest peak discharge is then used to simulate the overland flow using HEC-RAS 5.0.7, representing the most extreme condition when the dam break occurs. The generated flood induced by the dam break hit seven regencies with a total affected area of 1,596.59 km^2. Moreover, an economic analysis is conducted. The result states that the most affected regency by economic losses is Karawang Regency, and the least affected is Subang Regency. The financial analysis, conducted using the ECLAC method, shows that the extent of inundation influences economic losses due to flooding, the distribution of depth, and the land cover of the affected area. This study hopes to assist in developing a mitigation plan for future possible dam breaks and provide a recommendation for decision-makers for developing land use areas.**

***Keywords*— Dam break; cascade dam; economic loss; numerical modeling.**

Manuscript received 23 Aug. 2023; revised 4 Nov. 2023; accepted 13 Jan. 2023. Date of publication 29 Feb. 2024.

I. INTRODUCTION

Every dam has a possibility of failure, which geotechnical failure, earthquakes, errors in construction planning, etc. can cause. This may lead to a dam-break flood in the downstream areas, causing damage and loss of life, especially if the downstream area is urban [1]–[3]. Although significant dam break events are rare, they have been recorded to cause catastrophic damage [4], as shown in the devastating effect of the dam failure in the Mekong basin on its downstream area [5].

The Saguling, Cirata, and Jatiluhur dams make a cascade dam (hereon addressed as the Saguling-Cirata-Jatiluhur Dam), located in the Citarum River Basin. The upstream dam is the Saguling Dam, followed by the Cirata Dam, and then the Jatiluhur Dam. The damage caused by a cascade dam break is more severe, as there is more volume of water, and it may affect a larger area than the damage caused by a single dam [6]. Moreover, this cascade dam is one of the country's most valuable assets, as the Jatiluhur Dam is known to be the largest dam in Indonesia. Thus, the safety of cascade reservoirs has become an important consideration. Risk analysis to determine the possibility of a dam break occurrence is necessary for future disaster mitigation in water resources planning and management [7], [8]. Experience has shown that disaster mitigation implementation in the downstream area can drastically reduce the damage and loss of life.

Numerical modeling is an effective way to analyze and predict the dam break [9]. Physical modeling through laboratory experiments may provide more detailed results of the phenomenon. However, this method is usually more expensive and cannot offer variations in its modeling [10], [11]. Therefore, numerical modeling is preferred as the cost is lower and is easier to use while still providing good accuracy [12], [13]. Furthermore, numerical modeling can be utilized to investigate a complex situation [14], as they are often too complex to analyze without numerical models.

This study uses a two-dimensional simulation of flood propagation caused by the dam break of the Saguling-Cirata-Jatiluhur Dam to produce a flood inundation map with flood depth parameters. Dam break is simulated with several scenarios due to overtopping and piping. Using the scenario with the highest peak discharge, a two-dimensional numerical model is then used to simulate the overland flow generated by dam failure. This requirement represents the most extreme condition when the dam break occurs. By conducting this analysis, the disaster risk of the affected area can be determined.

The inundation result is then used for economic analysis using the ECLAC method. This analysis obtains the economic loss value due to the dam break of the cascade dam. Hopefully, this study on dam-break-induced flood routing of cascade reservoirs can provide theoretical support and a recommendation to improve risk aversion and safety performance of cascade reservoirs.

II. Materials and Method

A. Study Area

The Saguling-Cirata-Jatiluhur Dam is located in the West Java Province. This dam is situated mainly in the Citarum River. Downstream of these dams are densely populated areas, such as Karawang Regency, Bekasi Regency, and Purwakarta Regency. A dam break event may cause the community high financial and physical losses. The map of the study area is given in Fig. 1. The location of each dam is as follows:

- Saguling Dam
  Located in Batujajar District, West Bandung Regency, with coordinates 6°54'43.37"S and 107°21'58.28"E.
- Cirata Dam
  Located in Cirata District, West Bandung Regency, with coordinates 6°42'2.11"S and 107°22'1.81"E.
- Jatiluhur Dam
  Located in Jatiluhur District, Purwakarta Regency, with coordinates 6°31'23.28"S and 107°23'19.22"E.

B. Dam Watershed Characteristics

This research utilized DEM (Digital Elevation Model) data from Indonesia's Geospatial Information Agency. The spatial resolution of the DEM was 0.27 arcseconds. Meanwhile, the land cover data was from Indonesia's Ministry of Environment and Forestry. The reservoir bathymetry of the Saguling-Cirata-Jatiluhur Dam was determined based on topography data processed using GIS software.

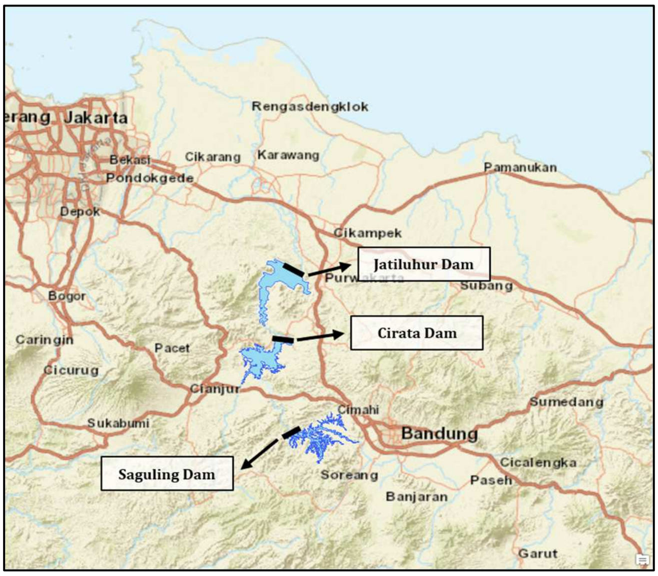

Fig. 1 Study Area

C. Methodology

The research methodology flowchart of this study is presented in Fig. 2. First, a hydrological analysis was carried out using the topographic data, land cover data, and rainfall data to calculate the PMF (Probable Maximum Flood) discharge. A dam break scenario for every dam was then developed using the dam's technical data to obtain the dam break parameters for each scenario.

Each dam break scenario's parameters were used for reservoir routing, which was conducted using HEC-HMS 4.6, reservoir bathymetry data, and PMF discharge. The output was dam break outflow discharge for every dam break scenario. The scenario with the highest peak discharge was considered the worst, which was then used as input for flood propagation modeling. The modeling was conducted using HEC-RAS 5.0.7.

HEC-HMS and HEC-RAS is a free license software developed by the US Army Corps of Engineers and has been widely used to simulate hydrology and hydraulic modeling in many studies [15]–[18]. The HEC-HMS software includes many traditional hydrologic analysis procedures, including the dam break simulation. Meanwhile, the HEC-RAS software allows the user to perform two-dimensional unsteady flow modeling. The model was developed based on the 2D Saint-Venant equations and solved using the finite difference method.

D. Hydrology Analysis

To obtain the PMF discharge, the watershed for each dam was first determined using the topographic data. The topographic data was processed using ArcGIS 10.5 to acquire the dam watershed characteristics, as in Table 1. The delineation results for each dam are shown in Fig. 3. Meanwhile, the land cover map is given in Fig. 4. The land cover data was used to define the watersheds' curve number (CN) coefficient and impervious number. The CN was chosen as the loss method for its accuracy and ease of application [19]. Research conducted by [20] also shows that the CN method provides the highest accuracy compared to other methods. The calculation results of CN and impervious number for each watershed are given in Table 2. The land cover data were also used to determine the surface roughness value (Manning value), as flood propagation is highly influenced by land cover [21], [22].

The PMF discharge was then calculated using PMP (Probable Maximum Precipitation) rainfall. As a standard, PMP rainfall for each watershed (RPMP) was obtained from the PMP Isohyet Map, published by the Ministry of Public Works of Indonesia. The values were as follows:

- Saguling, R_{PMP} = 520.57 mm
- Cirata, R_{PMP} = 583.03 mm
- Jatiluhur, R_{PMP} = 520.57 mm

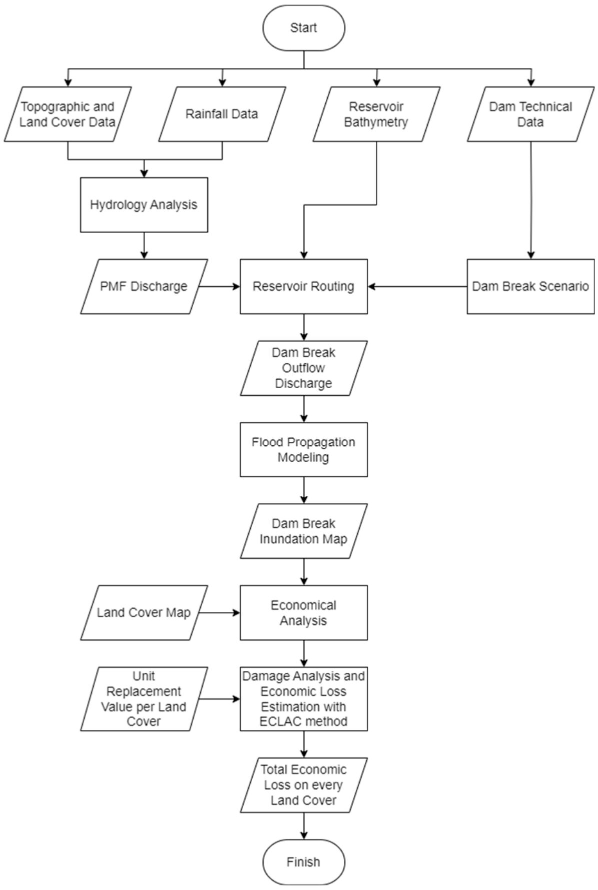

Fig. 2 Research Methodology Flowchart

The R_{PMP} was then multiplied with an ARF (areal reduction factor). ARFs convert point rainfall estimates to area-averaged estimates and are central to conventional flood risk assessment. This approach has been widely used in hydrologic and hydraulic modeling for flood hazard applications (e.g., inundation mapping and flood risk mitigation) [23]. Furthermore, to obtain adequate (mean) rainfall over a watershed, this adjustment is essential for characterizing rainfall-runoff relations and reducing precipitation volume when design storms are considered [24]. Error in the estimation of ARFs can result in significant errors in subsequent estimates of design rainfall and discharge [25].

Each region has a different ARF curve derived from the availability of data. The study area was located on Java Island. Therefore, the ARF for every dam watershed can be determined through the ARF Curve in Fig. 5, obtained from the Indonesia Standard Guideline for hydrology analysis. The ARF value for each dam watershed based on the curve is shown in Table 3. Moreover, the guideline also provides several rainfall distributions. One of the rainfall distribution standards used was the PSA-007 distribution. Therefore, PSA-007 was employed as the rainfall distribution with a rainfall duration of 6 hours. The results of the rain distribution calculation are given in Table 4.

TABLE I
DAM WATERSHED CHARACTERISTICS

Dam Watershed	Saguling Dam	Cirata Dam	Jatiluhur Dam
Area (km^2)	2,306.87	1,826.53	476.42
River Length (km)	75.97	114.44	107.74
Max. Elevation (m)	+ 2,577	+ 3,006	+ 1,731
Min. Elevation (m)	+ 611	+ 186	+ 39
Subbasin Slope	14.67 %	15.82 %	14.72 %
River Slope	2.26 %	1.38 %	1.71 %

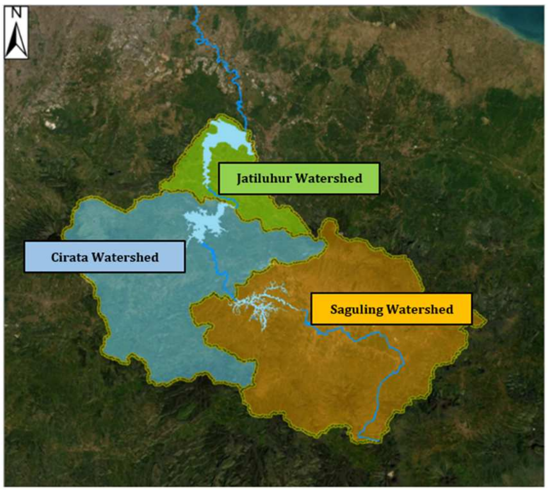

Fig. 3 Dam Watershed

The distributed rainfall was then used to calculate the PMF (Probable Maximum Flood) discharge, which is necessary for dam failure analysis. The PMF discharge (Q_{PMF}) was calculated using several Synthetic Unit Hydrograph (SUH) methods, such as Nakayasu (Alpha=2.0), SCS, ITB-1 (Exact), ITB-2 (Exact), ITB-1 (Numeric), ITB-2 (Numeric), and Snyder. Calculations were performed using the HEC-HMS software and inputting watershed characteristics. The model scheme is given in Fig. 6. The calculation results (hydrograph) are shown in Fig. 7, Fig. 8, and Fig. 9.

TABLE II
CURVE NUMBER AND IMPERVIOUS NUMBER

Dam Watershed	Saguling Dam	Cirata Dam	Jatiluhur Dam
Composite CN	80.37	80.86	85.51
Composite Imp.	21.13%	10.47%	9.33%

Although there have been many referable hydrograph models, there are still doubts about how to apply the models to Indonesia's tropical climate. This is because the characteristics in a tropical region vary between areas and the watershed response [26]. Thus, this study used the Creager diagram, developed by [27], to verify and select flood discharges from several SUH methods. The equation of the Creager diagram is shown in Equation (1).

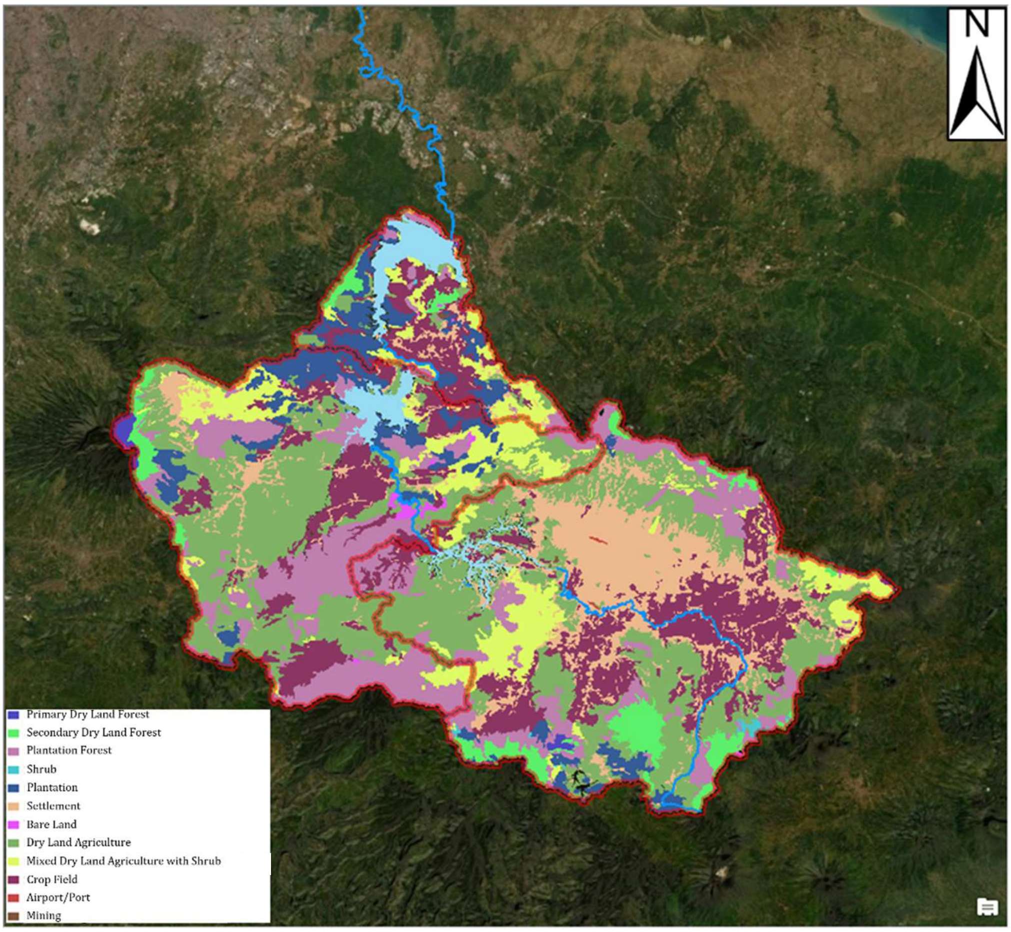

Fig. 4 Land Cover Map

$$Qp = 1.3\,C\left(\frac{A}{2.59}\right)^{0.894\left(\frac{A}{2.59}\right)^{-0.048}} \tag{1}$$

Where: Qp is peak discharge, C is the Creager coefficient, and A is the watershed area. This diagram is one of the most well-known methods and has been widely used in many hydrologic applications.

TABLE III
ARF VALUE OF DAM WATERSHED

Dam Watershed	Saguling Dam	Cirata Dam	Jatiluhur Dam
Area (km^2)	476.42	1,826.53	2,306.87
ARF	0.74	0.62	0.60

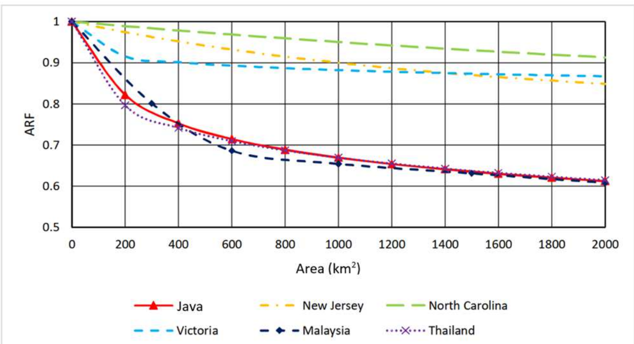

Fig. 5 ARF Curve of Several Regions

According to Indonesia Standard Guideline, the Creager coefficient for Java's PMF discharge is 120. The hydrograph method closest to Creager's QPMF is the Snyder SUH method. Therefore, the Snyder Hydrograph results were used as the dam inflow value. The Creager Diagram is shown in Fig. 10.

E. Reservoir Routing

The reservoir routing process was calculated using HEC-HMS and inputting three parameters: dam inflow, reservoir bathymetry, and dam breach parameters. The dam breach parameters for several dam failure scenarios were calculated after obtaining reservoir bathymetry through the GIS process and dam inflow through hydrology analysis.

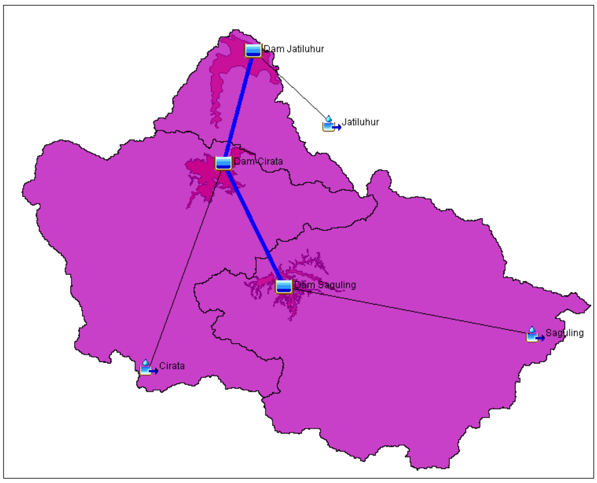

Fig. 6 HEC-HMS Hydrology Model Scheme

TABLE IV
RAINFALL DISTRIBUTION CALCULATION

Hour	Distribution (%)	R_{PMP} Saguling (mm)	R_{PMP} Cirata (mm)	R_{PMP} Jatiluhur (mm)
1	5	9.41	11.19	15.47
2	10	18.82	22.37	30.95
3	60	112.91	134.24	185.69
4	16	30.11	35.80	49.52
5	6	11.29	13.42	18.57
6	3	5.65	6.71	9.28
R_{PMP}		520.57	583.03	571.71
R_{PMP} x ARF		312.99	361.17	420.64

Each dam had 4 dam failure scenarios, differentiated by the cause of the failure: overtopping, top piping, middle piping, and bottom piping. The dam breach parameters were calculated based on a formula developed by [28], which included the breach side-slope ratio, average breach width, and breach formation time. The output was an outflow discharge due to the dam failure, which will be used as an input for the flood propagation modeling.

F. Flood Propagation Model

The flood propagation model was simulated using the HEC-RAS 5.0.7 two-dimensional model, which used the Saint-Venant equations as the governing equations. The equations consisted of a continuity equation and momentum equations, as shown in Equation (2)-(4).

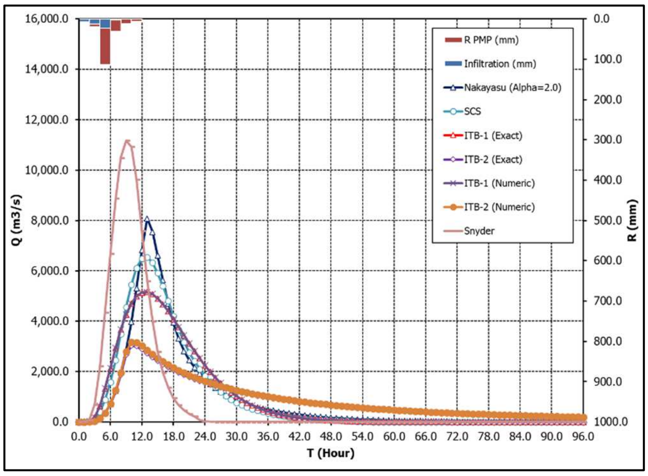

Fig. 7 Q_{PMF} of the Saguling Dam

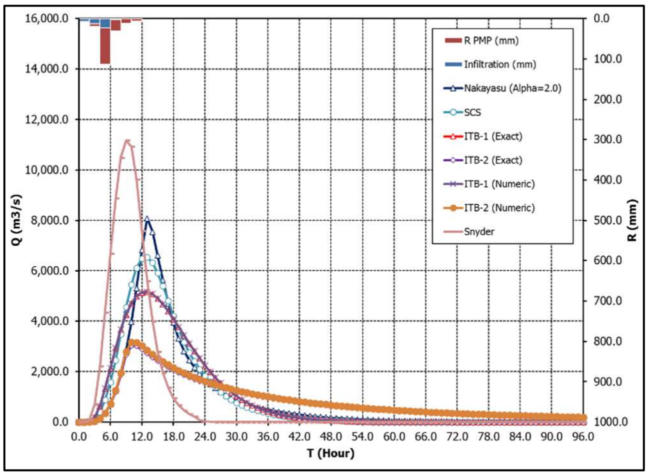

Fig. 8 Q_{PMF} of the Cirata Dam

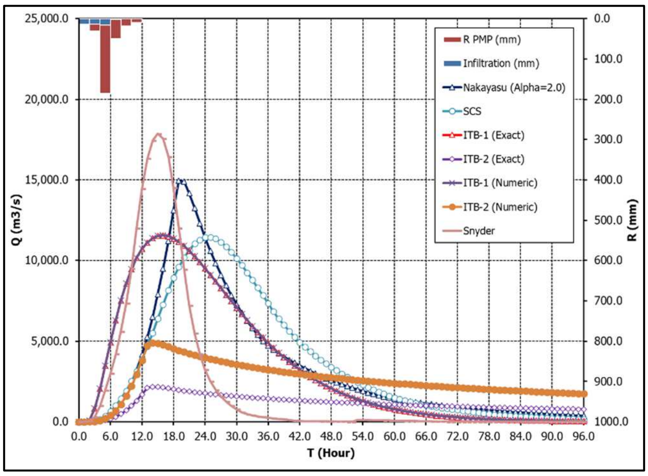

Fig. 9 Q_{PMF} of the Jatiluhur Dam

Continuity:

$$\frac{\partial h}{\partial t}+\frac{\partial (hu)}{\partial x}+\frac{\partial (hv)}{\partial y}=0 \quad (2)$$

Momentum x-direction:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+g\frac{\partial h}{\partial x}-g(So_x-Sf_x)=0 \quad (3)$$

Momentum y-direction:

$$\frac{\partial v}{\partial t}+v\frac{\partial v}{\partial y}+u\frac{\partial v}{\partial x}+g\frac{\partial h}{\partial y}-g\left(So_y-Sf_y\right)=0 \quad (4)$$

Where h is water depth, u and v are the velocity of the x-direction and y-direction respectively, g is the gravitational acceleration, Sox and Soy are the depth gradient for the x-direction and y-direction respectively, and Sfx and Sfy are energy grade lines for the x-direction and y-direction. To ensure the model stability, the time step was calculated according to the Courant-Friedrichs-Lewy condition, as shown in Equation (5).

$$Cr=\frac{c\Delta t}{\Delta x}=\frac{\sqrt{gh\Delta t}}{\Delta x}\leq 1 \quad (5)$$

The model grid size was set to 55 x 55 m for the Jatiluhur's upstream reservoir and 200 x 200 m for Jatiluhur's downstream reservoir. Meanwhile, the downstream's river size was set to 100 x 100 m using HEC-RAS's breakline feature. QPMF was used as the boundary conditions for each dam's upstream reservoir. Meanwhile, the downstream reservoirs used normal depth boundary conditions. The manning roughness is estimated for each type of land cover using coefficients from [29]. The HEC-RAS model scheme is shown in Fig. 11.

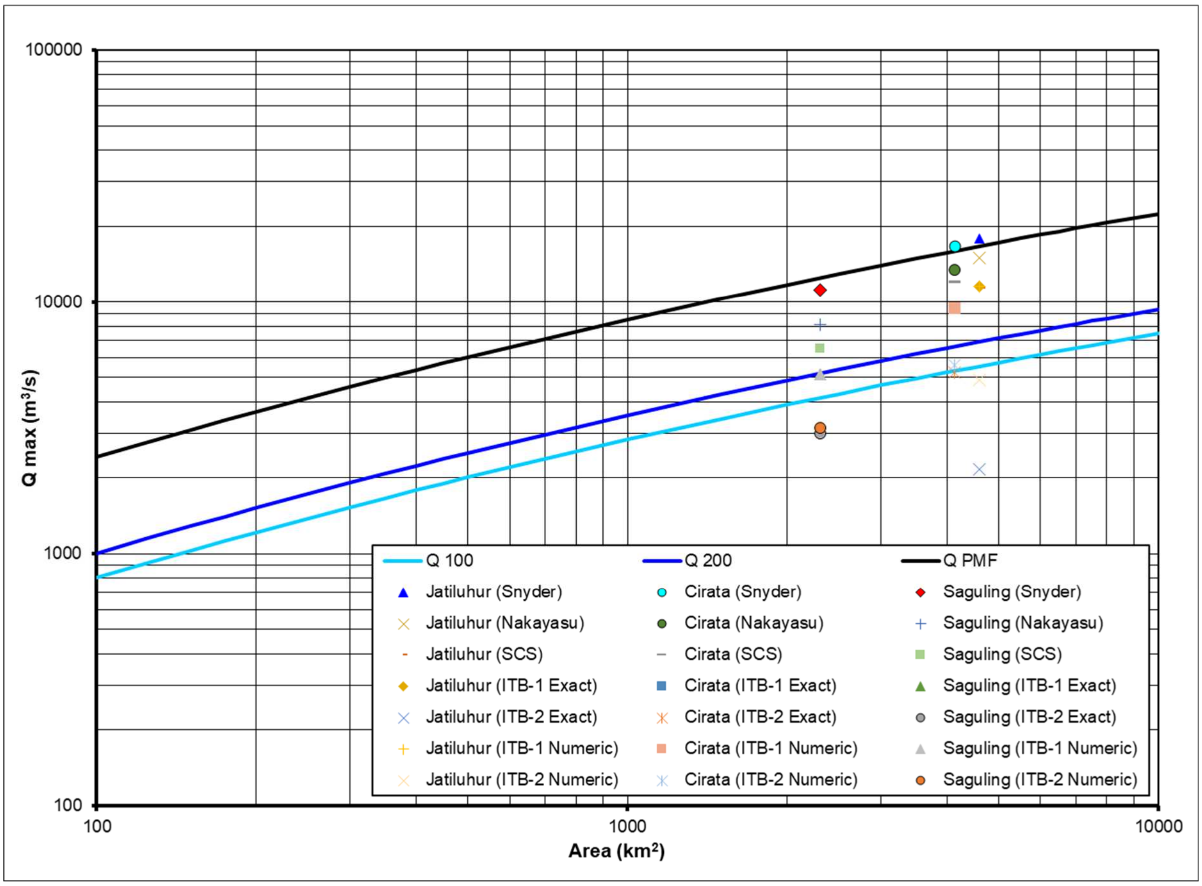

Fig. 10 Creager Diagram

TABLE V

DAM BREACH PARAMETERS FOR SAGULING DAM

Parameters	Scenario				Units
	Overtopping	Bottom Piping	Middle Piping	Top Piping	
Breach Side-Slope Ratio H:V	1 H : 1 V	0.7 H : 1 V	0.7 H : 1 V	0.7 H : 1 V	
Average Breach Width	292.5	292.5	292.5	292.5	m
Piping Coefficient	-	0.8	0.8	0.8	
Piping Elevation	-	580	601.75	643.00	
Breach Formation Time	1.82	1.82	1.82	1.82	hour
Trigger Elevation	650.50	650.50	650.50	650.50	m

TABLE VI

DAM BREACH PARAMETERS FOR CIRATA DAM

Parameters	Scenario				Units
	Overtopping	Bottom Piping	Middle Piping	Top Piping	
Breach Side-Slope Ratio H:V	1 H : 1 V	0.7 H : 1 V	0.7 H : 1 V	0.7 H : 1 V	
Average Breach Width	375.00	375.00	375.00	375.00	m
Piping Coefficient	-	0.8	0.8	0.8	
Piping Elevation	-	125.00	162.50	223.00	
Breach Formation Time	2.64	2.64	2.64	2.64	hour
Trigger Elevation	225.50	225.50	225.50	225.50	m

TABLE VII

DAM BREACH PARAMETERS FOR JATILUHUR DAM

Parameters	Scenario				Units
	Overtopping	Bottom Piping	Middle Piping	Top Piping	
Breach Side-Slope Ratio H:V	1 H : 1 V	0.7 H : 1 V	0.7 H : 1 V	0.7 H : 1 V	
Average Breach Width	253.5	253.5	253.5	253.5	m
Piping Coefficient	-	0.8	0.8	0.8	
Piping Elevation	-	46.90	72.25	111.50	
Breach Formation Time	3.68	3.68	3.68	3.68	hour
Trigger Elevation	114.50	114.50	114.50	114.50	m

III. Results and Discussion

A. Flood Propagation and Inundation

The dam breach parameters calculation results for every dam are given in Table 5, Table 6, and Table 7. The parameters were then used for the routing process using HEC-HMS. The results for each scenario of the routing process are given in Table 8. The maximum outflow discharge obtained by each dam was: Saguling Dam Break at 246,048.90 m^3/s due to bottom piping, Cirata Dam Break at 504,957.30 m^3/s due to overtopping, and Jatiluhur Dam Break at 478,109.50 m^3/s due to middle piping. These values became the inputs for flood propagation modeling, representing the most extreme conditions of a dam break.

The modeling results, a flood inundation map with parameters of flood depth is presented in Fig. 13. The generated flood induced by the dam break caused an inundation area of 1,596.59 km^2. The maximum inundation depth was approximately 20 m, with a maximum velocity of approximately 5 m/s. Moreover, the results showed that the flood was estimated to reach the estuary 40 hours from the start of the extreme rain.

TABLE VIII
Recapitulation of Peak Discharge Due to Dam Failure

Scenario	$Q_{outflow}$ (m^3/s) Saguling Dam	Cirata Dam	Jatiluhur Dam
Overtopping	-	**504,957.30**	438,903.60
Top Piping	98,785.70	210,633.50	306,992.20
Middle Piping	202,294.60	476,063.90	**478,109.50**
Bottom Piping	**246,048.90**	419,973.20	346,955.50

Spatial analysis was then carried out by overlaying the inundation area, land use, and the regency's administrative boundaries. Based on the results, there were 7 regencies affected by the floods, namely Subang, Purwakarta, Karawang, Cianjur, Bekasi, North Jakarta, Bandung, and West Bandung. The worst affected regency was Karawang, with an inundation area of 108,862.19 Ha. 8.13% of the settlements in the inundated area were affected. Meanwhile, the least affected regency was North Jakarta City with an inundation area of 4.83 Ha. 8.28% of settlements in the inundated area were affected.

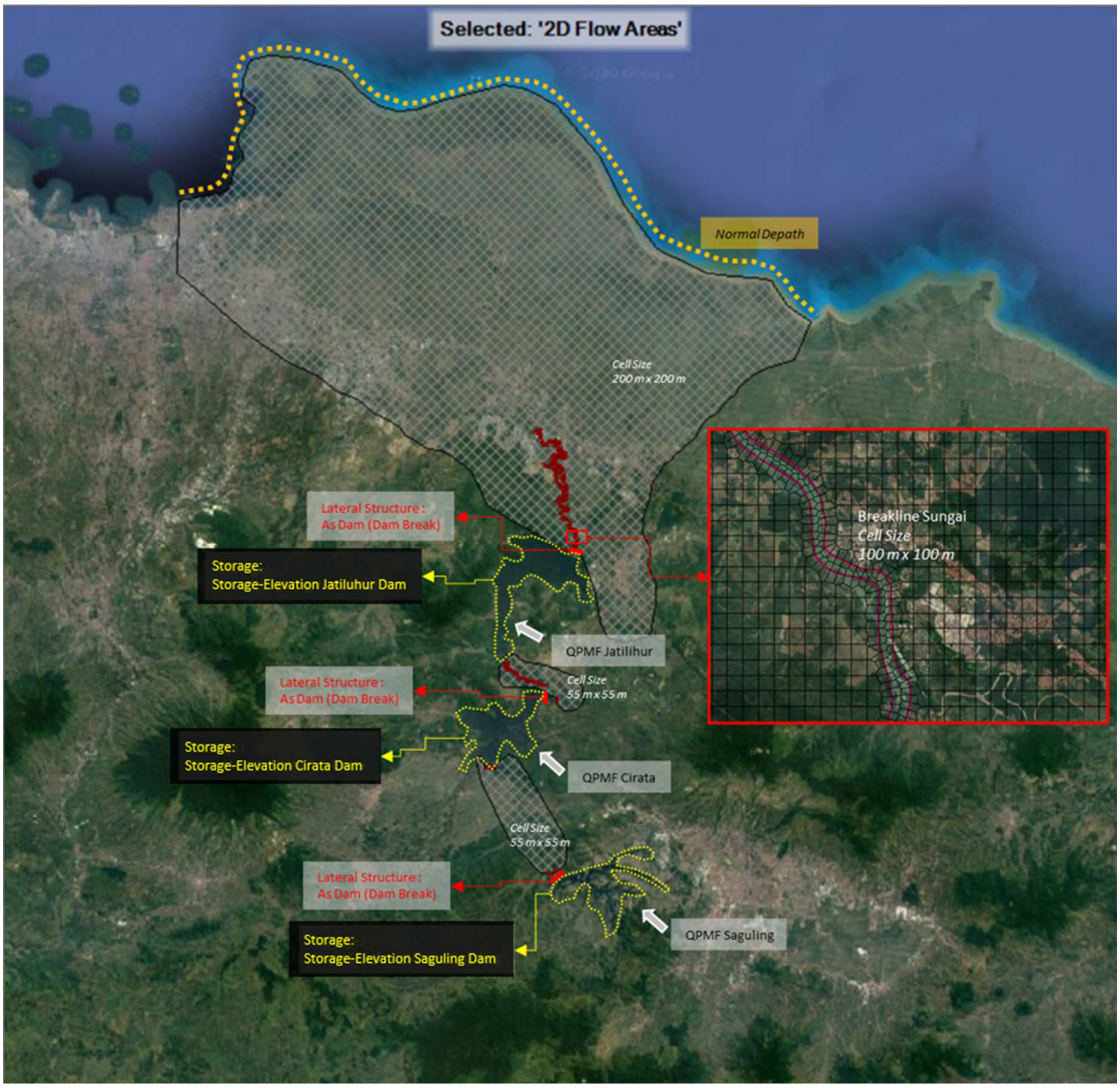

Fig. 11 HEC-RAS Model Scheme

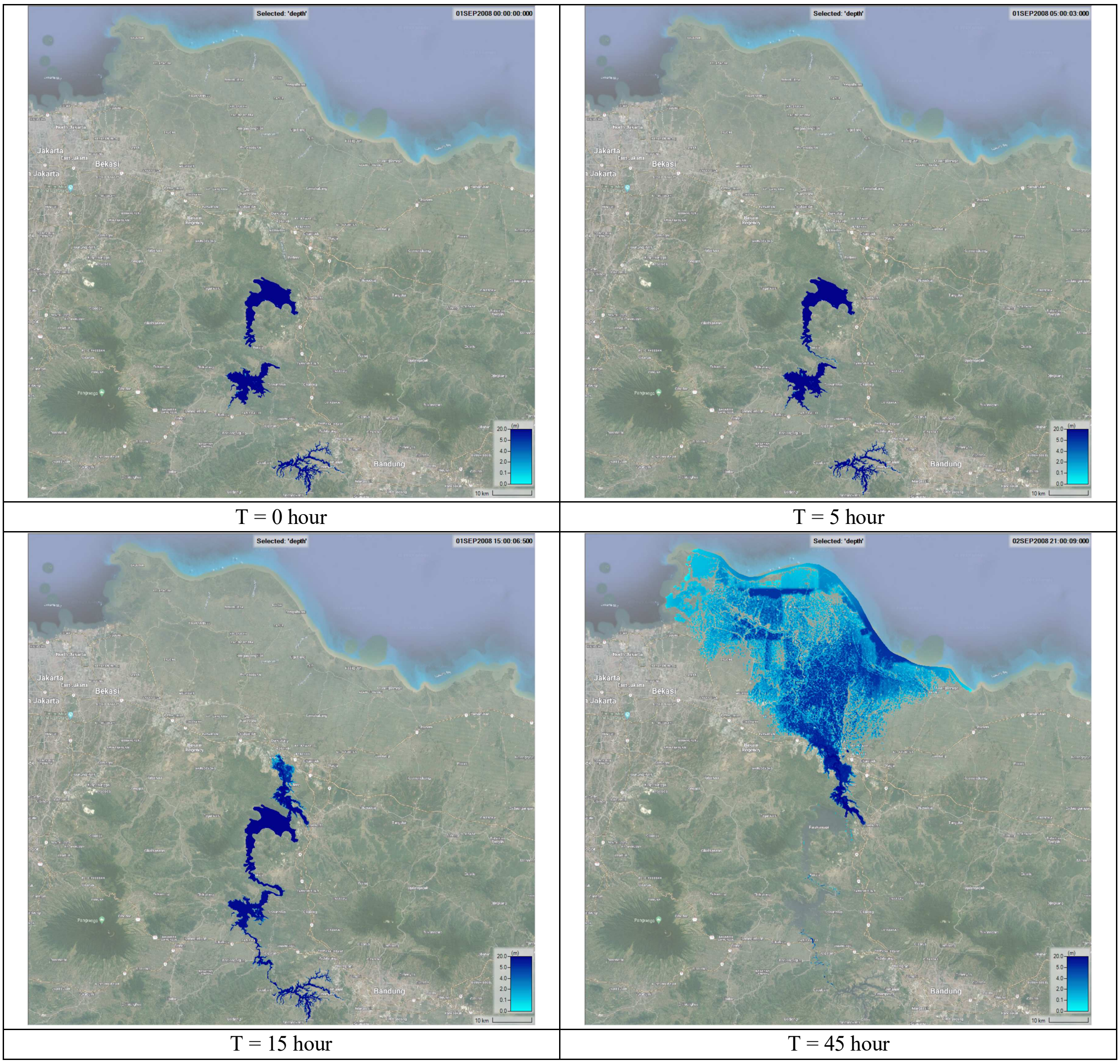

Fig. 12 Flood Propagation Progression

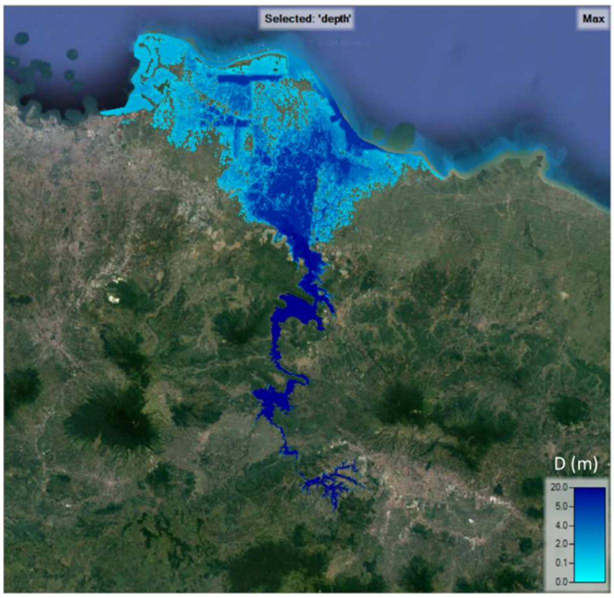

Fig. 13 Flood Depth Map

B. Economic Analysis

In economic analysis, several parameters are used, one of which is land cover. Land cover parameters were employed in the depth-damage function to analyze damage caused by a flood. The land cover used in the economic analysis was the 2019 land cover issued by the Ministry of Environment and Forestry of Indonesia. Based on the land cover analysis, every regency affected by the flood was dominated by agriculture, except North Jakarta. North Jakarta is 82.4% dominated by residential area, as shown in Table 9 and Table 10.

TABLE IX
LAND COVER AREA PER REGENCY

Land Cover	Land Cover Area (Ha)							Total
	Bekasi	Cianjur	North Jakarta	Karawang	Purwakarta	Subang	West Bandung	
Water Bodies	876.4	2354.0	0.0	1152.0	8667.1	349.3	6312.5	19711.3
Shrub	0.0	16.2	0.0	62.7	36.8	36.8	8.6	161.2
Forestry	0.0	120615.1	101.6	6731.4	18473.5	18473.5	49966.2	214361.1
Residentials	36616.7	8238.9	11277.4	26784.0	15920.1	15920.1	9995.3	124752.5
Agriculture	77443.5	83422.3	1418.5	130008.0	66460.7	159032.4	60931.6	578716.9
Open Space	3077.7	2378.7	60.2	8276.1	1224.7	6282.0	1150.6	22450.1
Pond	8299.0	0.0	485.4	18313.0	0.0	9720.0	1150.6	37967.9
Harbour	0.0	0.0	350.7	0.0	0.0	0.0	0.0	350.7
Mining Area	0.0	0.0	0.0	15.5	15.5	6.7	103.1	140.9

TABLE X
PERCENTAGE OF LAND COVER AREA PER REGENCY

Land Cover	Land Cover Percentage						
	Bekasi	Cianjur	North Jakarta	Karawang	Purwakarta	Subang	West Bandung
Water Bodies	0.7%	1.1%	0.0%	0.6%	7.8%	0.2%	4.9%
Shrub	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Forestry	0.0%	55.6%	0.7%	3.5%	16.7%	8.8%	38.5%
Residentials	29.0%	3.8%	82.4%	14.0%	14.4%	7.6%	7.7%
Agriculture	61.3%	38.4%	10.4%	67.9%	60.0%	75.8%	47.0%
Open Space	2.4%	1.1%	0.4%	4.3%	1.1%	3.0%	0.9%
Pond	6.6%	0.0%	3.5%	9.6%	0.0%	4.6%	0.9%
Harbour	0.0%	0.0%	2.6%	0.0%	0.0%	0.0%	0.0%
Mining Area	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%

The depth-damage function is usually derived through two methods. One is based on the damage data of past floods, and the other is from a hypothetical analysis based on land cover patterns, types of objects, information from a questionnaire survey, etc., known as synthetic stage-damage functions [30].

The Economic Commission for Latin America and the Caribbean (ECLAC) method calculates economic loss. The loss value is computed by multiplying the flood-affected area by the land's selling price and the depth-damage function. Though this method for estimating disaster losses has a significant tolerance value, it is thought to be lacking in essential factors, such as the building damage value. On the other hand, the technique developed by ECLAC is frequently employed in much research [31].

These synthetic depth–damage functions were developed through expert meetings and a workshop following the fuzzy cognitive mapping method [32]. The depth–damage functions show the fraction of the maximum economic exposure value per land use type that would result in damage at different inundation depths. Each land use class is assigned a value of economic exposure per hectare, as shown in Table 11. These values were derived via a series of expert meetings and a workshop [33].

Calculating economic losses due to flooding was carried out within the administrative border of a regency. There are 7 districts and cities affected by flooding due to dam break, as shown in Table 12. Moreover, Figure 14 illustrates the relationship between inundation depth and damage through seven different types of land cover.

TABLE XI
MAXIMUM ECONOMIC EXPOSURE PER LAND CLASSES

Land Use Class	Maximum Economic Exposure Value (Thousand USD/Ha)
Government Facility	301
Forestry	10.4
Industry and Warehouse	517.9
Commercial and Business	517.9
Residential	150.6
Agriculture	1.6
Swamp river and Pond	3.8
Open Space	3.1

Based on calculations, the worst affected area was Karawang Regency at $ 1,901,371,182.09 or Rp 28,520,567,731,383.30. The area with the lowest loss was Subang Regency at $ 992,132.96 or Rp 51,770,635,982.20. Based on calculations, North Jakarta City had the smallest inundation area, but the economic loss analysis showed that Subang Regency had the lowest economic loss. This may have happened because the land cover of North Jakarta City is dominated by residential area, resulting in greater economic loss.

Based on these results, it can be concluded that economic losses due to flooding are not only influenced by the extent of inundation but also by the distribution of depth and land cover in the affected area. Furthermore, this study can provide a recommendation for decision-makers in land use planning [34], such as developing residential areas in an area that has a low probability of flooding. This would decrease the economic loss caused by flooding.

TABLE XII
INUNDATION AREA AND ECONOMIC LOSS VALUE

Regency Name	Inundation Area (Ha)	Economic Loss (USD)	Economic Loss (IDR)
Karawang	107654.85	$ 1,901,371,182.09	Rp 28,520,567,731,383.30
Bekasi	40508.55	$ 406,875,016.00	Rp 6,103,125,239,969.11
Purwakarta	2814.04	$ 37,969,143.54	Rp 569,537,153,071.53
West Bandung	835.64	$ 4,930,207.43	Rp 73,953,111,506.90
Cianjur	644.15	$ 4,323,801.80	Rp 64,857,027,001.56
Subang	496.02	$ 992,132.96	Rp 14,881,994,443.57
North Jakarta	182.38	$ 3,451,375.73	Rp 51,770,635,982.20
Total	153135.64	$ 2,359,912,859.56	Rp 35,398,692,893,358.20

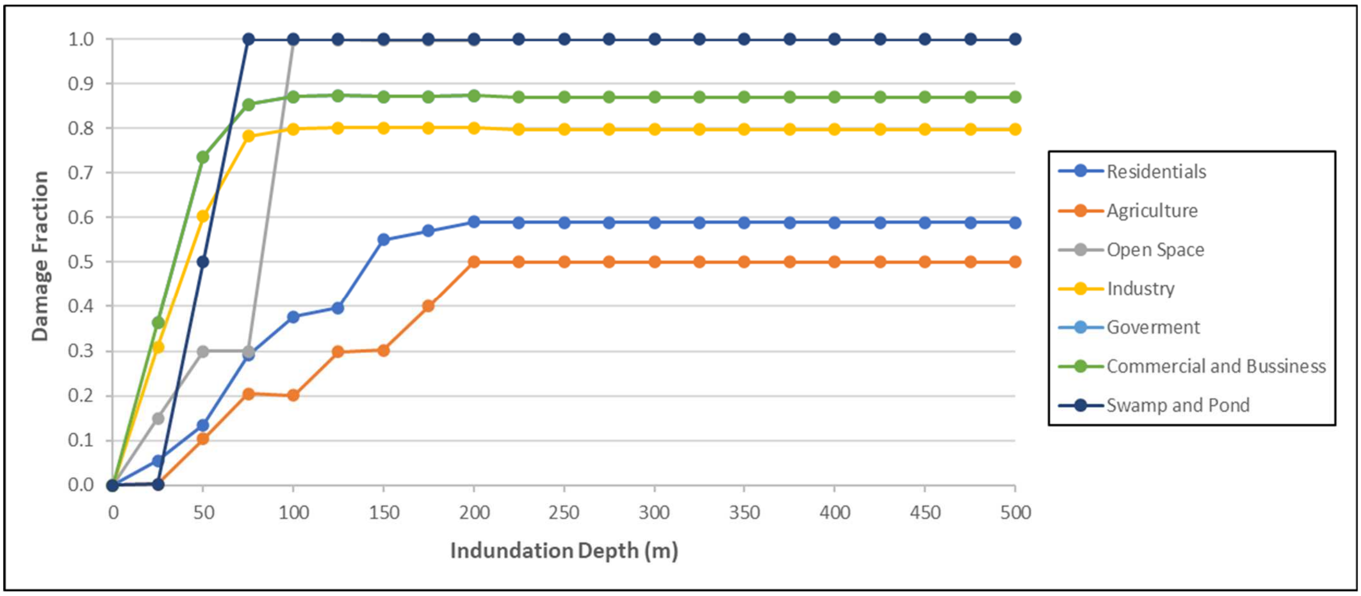

Fig. 14 Depth – Damage Function

IV. CONCLUSION

This study simulated flood propagation due to a dam break cascade of the Saguling-Cirata-Jatiluhur Dam to obtain an economic loss value. The dam break was first simulated using several scenarios based on the calculated dam breach parameters to obtain the dam-break outflow discharge. A two-dimensional numerical model was then used to simulate the overland flow generated by a dam failure, using the scenario of each dam with the highest peak discharge. This requirement represented the most extreme condition when the dam break occurred.

The generated flood induced by the worst dam break scenario caused an inundation in 7 regencies, affecting an area of 1,596.59 km^2, with a maximum inundation depth of approximately 20 m. Based on spatial analysis, the worst affected regency was Karawang, with an inundation area of 107,654.85 Ha. The least affected regency was North Jakarta City, with an inundation area of 182.38 Ha.

However, the results of the economic analysis showed that it is not North Jakarta City that had the most minor economic loss but Subang. Financial analysis revealed that the regency most affected by economic losses was Karawang, valued at $ 1,901,371,182.09 or Rp 28,520,567,731,383.30. The lowest economic loss was in Subang, valued at $ 992,132.96 or Rp 51,770,635,982.20.

Based on these results, it can be concluded that economic losses due to flooding were influenced by the extent of inundation and the distribution of depth and land cover in the affected area. This study's results can provide the necessary information to propose an effective mitigation plan. In addition, this study can provide a recommendation for decision-makers in developing an area, such as a residential area, in an area that is not affected or is not highly affected by a flood due to the failure of the Saguling-Cirata-Jatiluhur dam. This will reduce potential economic loss.

ACKNOWLEDGMENT

This study was supported by Institut Teknologi Bandung Research (Riset ITB), P2MI ITB, Riset Unggulan 3P, Program Riset Talenta Unggul LPIT ITB on Center for Water Resources Development, and PT. Reasuransi Maipark Indonesia.

REFERENCES

[1] J. Říha, S. Kotaška, and L. Petrula, "Dam break modeling in a cascade of small earthen dams: Case study of the Cizina River in the Czech Republic," *Water (Switzerland)*, vol. 12, no. 8, Aug. 2020, doi:10.3390/w12082309.

[2] A. Issakhov and Y. Zhandaulet, "Numerical study of dam break waves on movable beds for various forms of the obstacle by VOF method,"

Ocean Engineering, vol. 209, Aug. 2020, doi:10.1016/j.oceaneng.2020.107459.

[3] T. R. Maitsa, M. G. Indra Mardika, M. Bagus Adityawan, D. Harlan, D. Kusumastuti, and A. Adi Kuntoro, "2D numerical simulation of urban dam break and its effect to building using lax scheme with numerical filter," in *E3S Web of Conferences*, EDP Sciences, Mar. 2020. doi: 10.1051/e3sconf/202015604003.

[4] I. Magdalena and M. F. Eka Pebriansyah, "Numerical treatment of finite difference method for solving dam break model on a wet-dry bed with an obstacle," *Results in Engineering*, vol. 14, Jun. 2022, doi:10.1016/j.rineng.2022.100382.

[5] E. M. Latrubesse, E. Park, K. Sieh, T. Dang, Y. N. Lin, and S. H. Yun, "Dam failure and a catastrophic flood in the Mekong basin (Bolaven Plateau), southern Laos, 2018," *Geomorphology*, vol. 362, Aug. 2020, doi: 10.1016/j.geomorph.2020.107221.

[6] S. Takayama, M. Fujimoto, and Y. Satofuka, "Amplification of flood discharge caused by the cascading failure of landslide dams," *International Journal of Sediment Research*, vol. 36, no. 3, pp. 430–438, Jun. 2021, doi: 10.1016/j.ijsrc.2020.10.007.

[7] T. Wang *et al.*, "Risk consequence assessment of dam breach in cascade reservoirs considering risk transmission and superposition," *Energy*, vol. 265, Feb. 2023, doi: 10.1016/j.energy.2022.126315.

[8] S. Oguzhan and A. O. Aksoy, "Experimental investigation of the effect of vegetation on dam break flood waves," *Journal of Hydrology and Hydromechanics*, vol. 68, no. 3, pp. 231–241, Sep. 2020, doi:10.2478/johh-2020-0026.

[9] Q. Hafiyyan, D. Harlan, M. B. Adityawan, D. K. Natakusumah, and I. Magdalena, "2D Numerical Model of Sediment Transport Under Dam-break Flow Using Finite Element," *Int J Adv Sci Eng Inf Technol*, vol. 11, no. 6, pp. 2476–2481, 2021, doi: 10.18517/ijaseit.11.6.14484.

[10] K. Firdaus, A. M. A. Matin, N. Nurisman, and I. Magdalena, "Numerical study for Sunda Strait Tsunami wave propagation and its mitigation by mangroves in Lampung, Indonesia," *Results in Engineering*, vol. 16, Dec. 2022, doi: 10.1016/j.rineng.2022.100605.

[11] I. Magdalena *et al.*, "Numerical Study on Wave Run-up to Identify the Most Effective Design of Jakarta's Outer Sea Dike," *Int J Adv Sci Eng Inf Technol*, vol. 12, no. 1, pp. 202–208, 2022, doi:10.18517/ijaseit.12.1.12613.

[12] M. B. Adityawan *et al.*, "Numerical modeling of dam break induced flow through multiple buildings in an idealized city," *Results in Engineering*, vol. 18, Jun. 2023, doi: 10.1016/j.rineng.2023.101060.

[13] C. Chumchan and P. Rattanadecho, "Experimental and numerical investigation of dam break flow propagation passed through complex obstacles using LES model based on FVM and LBM," *Songklanakarin J Sci Technol*, vol. 42, no. 3, pp. 564–572, 2020, doi: 10.14456/sjst-psu.2020.71.

[14] S. Kocaman, H. Güzel, S. Evangelista, H. Ozmen-Cagatay, and G. Viccione, "Experimental and numerical analysis of a dam-break flow through different contraction geometries of the channel," *Water (Switzerland)*, vol. 12, no. 4, Apr. 2020, doi: 10.3390/W12041124.

[15] R. M. Fadillah, H. Tsaqib, A. K. Nurendyastuti, M. Jannah, and R. M. S. Prastica, "Structural mitigation measures for flood reduction in urban area: A case study of Ciliwung watershed," in *E3S Web of Conferences*, EDP Sciences, Oct. 2020. doi:10.1051/e3sconf/202020001004.

[16] M. A. Afzal *et al.*, "Flood Inundation Modeling by Integrating HEC–RAS and Satellite Imagery: A Case Study of the Indus River Basin," *Water (Switzerland)*, vol. 14, no. 19, Oct. 2022, doi:10.3390/w14192984.

[17] S. J. Zeiger and J. A. Hubbart, "Measuring and modeling event-based environmental flows: An assessment of HEC-RAS 2D rain-on-grid simulations," *J Environ Manage*, vol. 285, May 2021, doi:10.1016/j.jenvman.2021.112125.

[18] M. A. M. Razi, M. A. Z. Deli, M. A. M. Yusoff, M. A. Ahmad, and M. S. Adnan, "Flood Modelling Studies Using River Analysis System (HEC-RAS) For Flood Plain Area in Muar City," *International Journal of Integrated Engineering*, vol. 14, no. 9, pp. 38–47, 2022, doi:10.30880/ijie.2022.14.09.006.

[19] M. Farid, M. I. Pratama, A. A. Kuntoro, M. B. Adityawan, F. I. W. Rohmat, and I. R. Moe, "Flood Prediction due to Land Cover Change in the Ciliwung River Basin," *International Journal of Technology*, vol. 13, no. 2, pp. 356–366, 2022, doi: 10.14716/ijtech.v13i2.4662.

[20] M. I. Pratama, F. I. W. Rohmat, M. Farid, M. B. Adityawan, A. A. Kuntoro, and I. R. Moe, "Flood hydrograph simulation to estimate peak discharge in Ciliwung river basin," in *IOP Conference Series: Earth and Environmental Science*, IOP Publishing Ltd, Apr. 2021. doi:10.1088/1755-1315/708/1/012028.

[21] M. R. Purnama, M. B. Adityawan, M. Farid, and A. Chrysanti, "Effectiveness of an Elevated Road in Reducing Inundation Area of the Coast of Palu, Sulawesi, Indonesia," *Journal of Disaster Research*, vol. 17, no. 7, pp. 1127–1139, Dec. 2022, doi:10.20965/jdr.2022.p1127.

[22] M. B. Adityawan, P. Rahmasari, A. Chrysanti, M. Farid, B. P. Yakti, and M. R. Purnama, "Effect of Land Cover on Tsunami Overland Flow Propagation: A Case Study of Painan, West Sumatra, Indonesia," *Int J Adv Sci Eng Inf Technol*, vol. 11, no. 5, pp. 1704–1712, 2021, doi:10.18517/ijaseit.11.5.14261.

[23] S. C. Kao, S. T. DeNeale, E. Yegorova, J. Kanney, and M. L. Carr, "Variability of precipitation areal reduction factors in the conterminous United States," *J Hydrol X*, vol. 9, Dec. 2020, doi:10.1016/j.hydroa.2020.100064.

[24] R. Joseph, P. P. Mujumdar, and R. Das Bhowmik, "Reconstruction of Urban Rainfall Measurements to Estimate the Spatiotemporal Variability of Extreme Rainfall," *Water (Switzerland)*, vol. 14, no. 23, Dec. 2022, doi: 10.3390/w14233900.

[25] D. B. Wright, J. A. Smith, and M. L. Baeck, "Critical Examination of Area Reduction Factors," *J Hydrol Eng*, vol. 19, no. 4, pp. 769–776, Apr. 2014, doi: 10.1061/(asce)he.1943-5584.0000855.

[26] A. R. Suleman, H. Djufri, M. R. Mustamin, and M. L. Palembangan, "Structural Mitigation of Bila River, Sidrap Regency," *Turkish J. Computer and Mathematics Education*, vol. 12, no. 6, pp. 3573–3577, 2021.

[27] W. P. Creager, J. D. Justin, and J. Hinds, "Engineering for Dams: Volume 1 – General Design," John Wiley and Sons, New York, 1945.

[28] D. C. Froehlich, "Embankment Dam Breach Parameters and Their Uncertainties," *Journal of Hydraulic Engineering*, vol. 134, no. 12, pp. 1708–1721, Dec. 2008, doi:10.1061/(asce)0733-9429(2008)134:12(1708).

[29] V. T. Chow, "Open-Channel Hydraulics," McGraw-Hill Book Company, New York, 1959.

[30] I. M. Khairul, M. Rasmy, M. Ohara, and K. Takeuchi, "Developing Flood Vulnerability Functions through Questionnaire Survey for Flood Risk Assessments in the Meghna Basin, Bangladesh," *Water (Switzerland)*, vol. 14, no. 3, Feb. 2022, doi: 10.3390/w14030369.

[31] N. R. Chayyani, E. Gravitiani, and Suryanto, "Socio-economic vulnerability and losses of flood in Lampung, Indonesia," in *IOP Conference Series: Earth and Environmental Science*, Institute of Physics Publishing, Jan. 2020. doi: 10.1088/1755-1315/423/1/012054.

[32] P. P. Groumpos, "Fuzzy Cognitive Maps: Basic Theories and Their Application to Complex Systems," in *Fuzzy Cognitive Maps: Advances in Theory, Methodologies, Tools and Applications*, M. Glykas, Ed., Berlin, Heidelberg: Springer Berlin Heidelberg, 2010, pp. 1–22. doi: 10.1007/978-3-642-03220-2_1.

[33] Y. Budiyono, J. Aerts, J. J. Brinkman, M. A. Marfai, and P. Ward, "Flood risk assessment for delta mega-cities: a case study of Jakarta," *Natural Hazards*, vol. 75, no. 1, pp. 389–413, Jan. 2015, doi:10.1007/s11069-014-1327-9.

[34] M. Farid, B. Gunawan, M. S. Badri Kusuma, S. A. Habibi, and A. Yahya, "Assessment of flood risk reduction in Bengawan Solo River: A case study of Sragen Regency," *International Journal of Geomate*, vol. 18, no. 70, pp. 229–234, 2020, doi:10.21660/2020.70.18010.