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The Impact of Dam Reservoir on Flood Reduction (Case Study Logung Reservoir, Kudus, Central Java)

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ABSTRACT

The Indonesian government targeted building 65 reservoirs and dams in 2015-2022. The purpose is to maintain food security facing the long-term climate crisis, besides reducing the impact of a flood. Logung Reservoir is located on the Logung River, Kudus, Central Java. This earth-fill dam was built to solve the flood and drought problems in Kudus. However, the existence of the Logung Reservoir gives a risk to the downstream area. The purpose of this research is to study flood reduction and the risk of overtopping, which can cause a dam break, and to calculate the Logung Reservoir spillway's performance in handling floods. This study is based on four main steps: the rainfall-runoff modelling, the extreme rainfall estimation, the hydrograph inflow of the dam estimation, and the evaluation of food reduction. The results of the 1000-year rainfall analysis and PMP for the Logung dam basin were 409 mm and 704 mm, respectively. Rainfall distribution is made using ABM, and effective rainfall is calculated by the SCS method. Land use analysis in the Logung dam watershed obtained a CN-II of 71.4 and a CN-III of 85.2. The rainfall-runoff transformation method used a unit hydrograph. The Nakayasu and Gama-I unit hydrographs show significant differences from the peak discharge, although not for the time base. The flood hydrograph design affects the reservoir performance. The reservoir flood routing results in a dumping efficiency of 35% for the 1000-year and 21% for PMF. The 1000-year flood routing shows that there was no risk of overtopping. The highest water level on the PMF flood routing at +94.1. Several solutions can prevent overtopping by reducing inflow discharge through small dams upstream, increasing the green area, or modifying spillway structure.

1. Introduction

Flood is a disaster that often occurs during the rainy season due to big storms, especially in urban areas. Globally, flooding is projected to increase due to climate change and population growth [1]. A dam has an impact on the management of water resources [2]. The presence of dams significantly influences the estimation of a population's exposure to future flooding, emphasizing the need to integrate them in model-based climate change impact analyzes [1].

The Indonesian government targeted building 65 reservoirs and dams in 2015-2022. The purpose is to maintain food security facing the long-term climate crisis, besides reducing the impact of a flood. Dams can reduce flood by the reservoir characteristic. The evaluation of flood reduction needs to be done to determine the effectiveness of the hydraulic spillway structure of the dam.

Dams can be classified into three types: concrete dams, earth-fill dams, and rockfill dams [3]. More than 90% of dams in Indonesia are earth-fill type [4]. The weakness of an earth-fill dam is that it cannot resist an overtopping at the top of the dam. Overtopping can cause the collapse of an earth-fill dam [5]. A spillway is constructed to prevent overtopping and functions as a flood overflow or a dam safety component. The spillway's capacity is affected by the spillway's dimensions without considering the outflow from the outlet [6].

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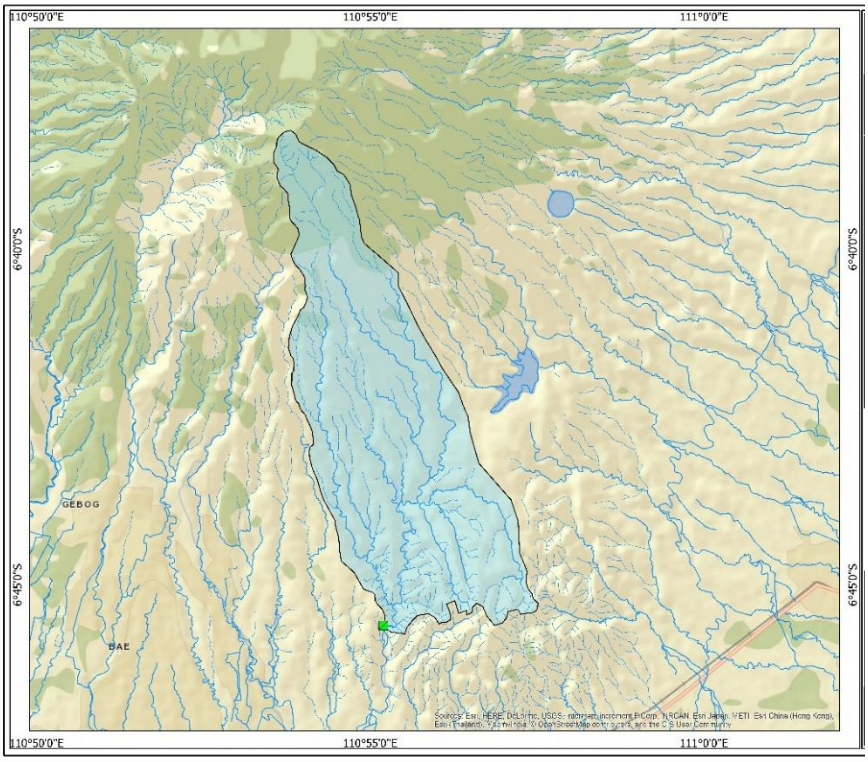

Figure 1. Logung Watershed

Logung Reservoir is located on the Logung River, Kudus Regency. This earth-fill dam was built to solve the flood and drought problems in Kudus. However, the existence of the Logung Reservoir gives a risk to the downstream area. The purpose of this research is to study flood reduction and the risk of overtopping, which can cause a dam break, and to calculate the Logung Reservoir spillway's performance in handling floods.

2. Methods

2.1 Study Area

The Logung dam is a hydraulic structure built in Logung river basin to solve the flood and drought problem in Kudus, Central Java. The dam centerline is located at 110^{O} 55' 20.27" Longitude and 06^{O} 45' 28.38" Latitude. This 55 m dam inundated the Dukuh Sintru area with an inundation area of 144.06 Ha with a storage capacity of 20.15 Mm^3. The basin's total area of 43.81 km^2, as illustrated in Figure 1.

The climate in the study location is a tropical area influenced by the West Monsoon and South Monsoon. This area has an average temperature between 23°C to 24°C with annual precipitation of 2205 mm. Most area in this basin is covered by 77% of agricultural area, 11% of an urban area, 8% of forest, and 4% of bare soil. Due to the large area of agricultural land surrounding the study area, the existence of the Logung dam is very beneficial for the sustainability of agriculture. The Logung Dam is classified as a downstream high-risk hazard based on the number of risk populations. Therefore, this study investigates the potential overtopping that causes dam-break during extreme floods.

The Logung flood routing model procedures illustrates as follows:

1. Modelling the rainfall-runoff of Logung Basin with a unit hydrograph.
2. Estimating the extreme rainfall frequency analysis using the annual maximum rainfall data.
3. Estimating the peak inflow of the dam for the 1000-year and PMF.
4. Evaluating the impact of the dam reservoir on flood reduction.

2.2 Data Collection

The rainfall data collected from Gembong, Tanjung Rejo, and Rahtawu station from 1970 – 2009 (40 years). Area rainfall of the Logung basin was calculated using the Thiessen. The monthly streamflow data collected from 1990 to 2012.

The reservoir characteristics will work on the outflow of the spillway. The storage-discharge relationship is required to model a reservoir in the flood routing analysis [7]. The Logung reservoir characteristics were obtained from the

Pemali Juana River Basin Organization. The data collected for flood routing analysis at least: the stage-discharge relationship and the elevation-storage relationship as shown at Figure 2.

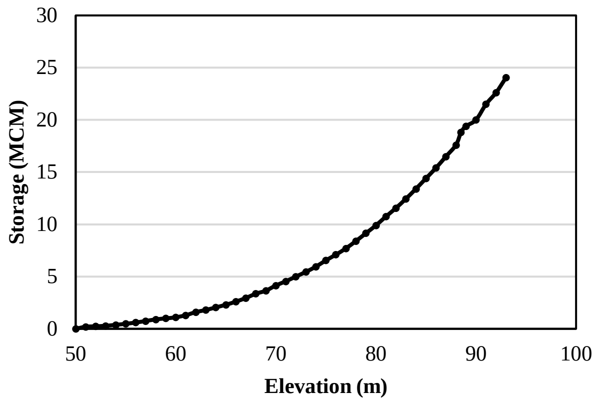

Figure 2. Stage-storage rating curve [8]

The reservoir storage (S) at specific elevation (E) was generated from Figure 2 given by Equation 1.

$$S=0.0161E^2 - 1.7744E + 49.366 \quad (1)$$

2.3 Frequency Analysis

The calculation of the rainfall probability is conducted by the frequency analysis method. A frequency analysis is a statistical approach for estimating the rainfall probability. This research considers four statistical distributions: Normal distribution, Log Normal, Gumbel, and Log Pearson III. The statistical parameters used in the frequency analysis include average rainfall (X), standard deviation (Sd), coefficient of variation (Cv), coefficient of skewness (Cs), and kurtosis coefficient (Ck). The most suitable statistical distribution must choose to avoid overestimating or underestimating rainfall. For this reason, it is necessary to carry out a goodness of fit test. There are two goodness of fit tests, such as the Smirnov Kolmogorov and the Chi-Square [9].

2.4 Probable Maximum Precipitation (PMP)

One of the design parameters in the spillway is the Probable Maximum Flood (PMF). The Probable Maximum Precipitation (PMP) needed to generate the PMF. In this study, the PMP is estimated with WMO guidelines No. 1045 [10]. The PMP was calculated using the statistical Hershfield method. The equations used in the Hershfield method are the developed frequency equation from Chow written in Equation 2 to Equation 4.

$$P_m=X_{n'}+K_m.S_{n'} \quad (2)$$
$$X_{n'}=f_1.f_2.X_n \quad (3)$$
$$S_{n'}=f_3.f_4.S_n \quad (4)$$

with P_m represent the probable maximum precipitation, $X_{n'}$ is the adjusted mean daily rainfall series, K_m is the coefficient based on rainfall duration and mean annual maximum rainfall, $S_{n'}$ is the adjusted standard deviation of the daily rainfall series, S_n is the standard deviation of the daily rainfall series, X_n is the mean daily rainfall series, $f1$ and $f2$ is the mean adjustment factor, and f_3 and f_4 is the standard deviation adjustment factor. Then, the PMP is adjusted for 24 hours or more rainfall data by multiplying by a factor of 1.3.

2.5 Rainfall Distribution

Rainfall design distribution is made by Alternating Block Method (ABM). The ABM method requires short-duration rainfall data. If short-duration rainfall data is unavailable, the Mononobe derives the equation to develop the intensity duration frequency (IDF) curve [5], [9].

$$I_t=\frac{R_{24}}{24}\left(\frac{24}{t}\right)^{2/3} \quad (5)$$

Where I_t represent the rainfall intensity for duration t, R_{24} is daily rainfall, and t is the rainfall duration.

Rainfall duration is approached by the time of concentration [11]. The time concentration (T_c) can be calculated using several equations, such as Kirpich (Equation 8) and Australian Rainfall-Runoff (Equation 9).

$$T_c = 0.6628L^{0.77}S^{-0.385} \quad (8)$$
$$T_c = 0.76A^{0.38} \quad (9)$$

With T_c is the time concentration (hours), A is the catchment area (km^2), L is the flow length (km), and S is the slope of catchment area.

2.6 Effective Rainfall

The SCS method is used to calculate effective rainfall. Effective rainfall is the rainfall that becomes runoff. The equations used in the SCS method are shown in Equation 7 and Equation 8.

$$P_e=\frac{(P-Ia)^2}{P-Ia+S} \quad (7)$$
$$Ia = 0.2\ S \quad (8)$$

With P_e is the effective rainfall (mm), P is the rainfall, Ia is the initial abstraction, and S is the maximum potential retention. The maximum potential retention is obtained from Equation 9.

$$S=\frac{25400}{CN}-254 \tag{9}$$

The curve Number (CN) used in Equation 9 is CN-II for normal conditions (AMC II). For wet conditions (AMC III), the CN-III can be derived from the CN-II by Equation 10.

$$CN(III)=\frac{23CN(II)}{10+0.13CN(II)} \tag{10}$$

2.7 Unit Hydrograph

A unit hydrograph is a direct runoff hydrograph generated by effective rainfall in a watershed with a fixed intensity in a time unit [12]. The unit hydrograph used in this study is Nakayasu and Gama-I.

The Nakayasu unit hydrograph was developed based on the characteristics of rivers in Japan. The Gama-I Synthetic Unit Hydrograph was developed based on the hydrological behavior of 30 watersheds in Java Island. Recently it has proven to function well in other regions in Indonesia [13].

2.8 Reservoir Flood Routing

Reservoir flood routing uses the water balance principle expressed in Equation 12 and 13. The gap between the inflows and outflows of the reservoir is equal to the storage changes during a time interval.

$$I - O = \Delta S \tag{12}$$

$$\frac{I_1+I_2}{2}\Delta t - \frac{O_1+O_2}{2}\Delta t = \Delta S \tag{13}$$

With I_1 represent the inflow at the start of time step, O_1 is the outflow at the start of time step, S_1 is the storage at the start of time step, I_2 the inflow at the end of time step, O_2 is the outflow at the end of time step, S_2 is the storage at the end of time step, and Δt is the change of time. The S and O determination use stage and storage relation as Equation 1.

4. Results and Discussions

The 40-years annual maximum rainfall and statistical parameter results are presented in Table 1 and Table 2. This result is used to calculate PMP by the Hersfield method. The statistical Hershfield requires the mean and standard deviation correction coefficient and statistical coefficient. These coefficients are obtained from the graph in WMO No. 1045 [10] as Figure 3 to Figure 6. The summary of hershfield coefficients shown in Table 3.

Table 1. Annual maximum rainfall of Logung Basin.

No	Year	Annual rainfall (mm)	No	Year	Annual rainfall (mm)
1	1970	108	21	1990	84
2	1971	151	22	1991	89
3	1972	118	23	1992	63
4	1973	135	24	1993	78
5	1974	129	25	1994	75
6	1975	117	26	1995	59
7	1976	121	27	1996	76
8	1977	131	28	1997	85
9	1978	82	29	1998	98
10	1979	72	30	1999	124
11	1980	91	31	2000	90
12	1981	139	32	2001	101
13	1982	81	33	2002	282
14	1983	74	34	2003	111
15	1984	113	35	2004	128
16	1985	201	36	2005	72
17	1986	103	37	2006	112
18	1987	84	38	2007	96
19	1988	100	39	2008	162
20	1989	75	40	2009	143

Table 2. Statistical parameters

Statistical parameters	
Number of data	40
Mean (X_n)	109
Mean without maximum (X_{n-m})	104.38
Standard Deviation (S_n)	40.926
Standard deviation without maximum (S_{n-m})	30.16
Skewness Coefficient(C_s)	2.247
Kurtosis Coefficient(C_k)	7.512
Coefficient of Variation (C_v)	0.376
Median	100.5

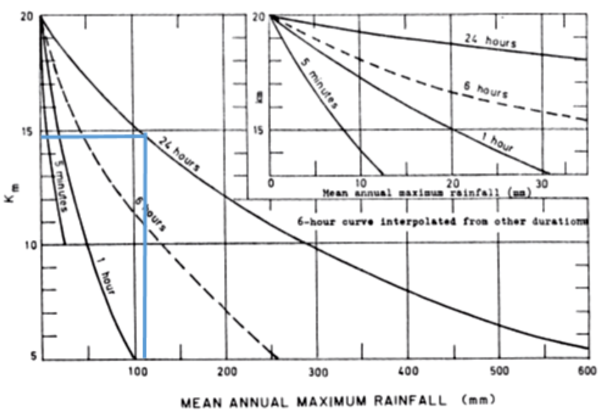

Figure 3. Determination of K_m

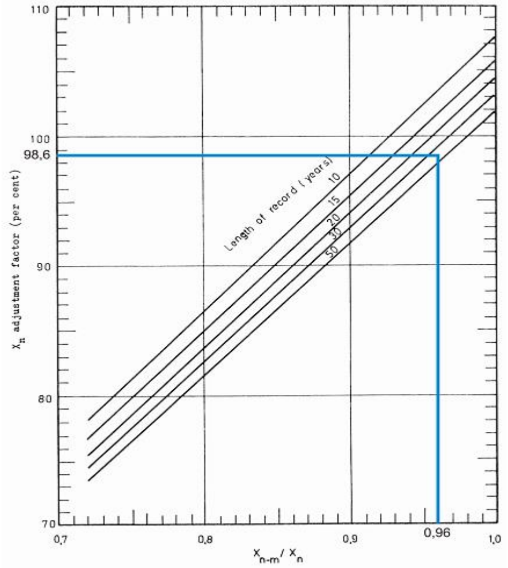

Figure 4. Determination of f_1

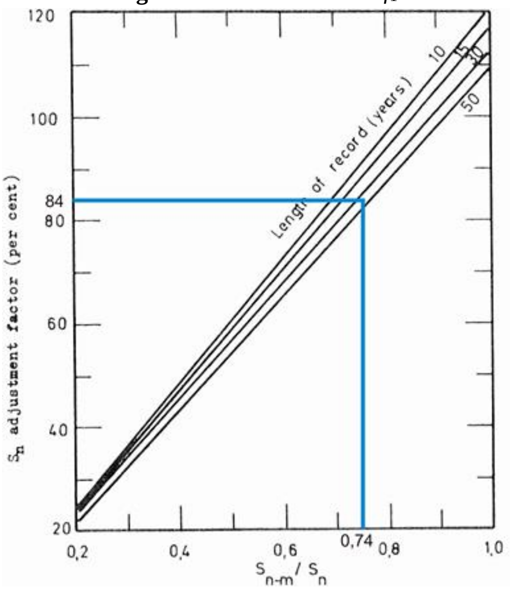

Figure 5. Determination of f_3

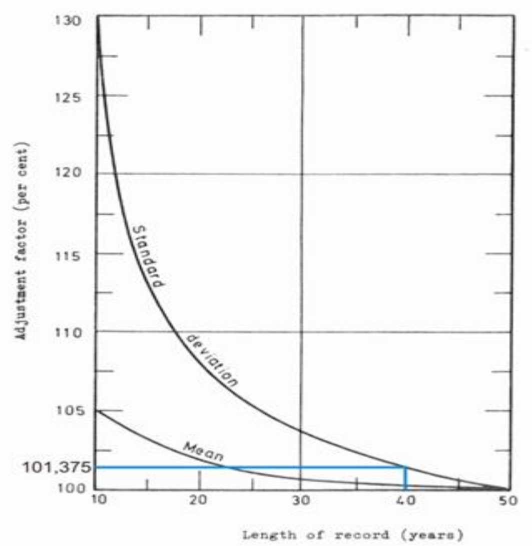

Figure 6. Determination of f_1 and f_4

Table 3. Hersfield coefficient factor

No	Hershfield coefficient factor	
1	*Km*	14.8
2	f_1	0.986
3	f_3	0.84
4	f_4	1.01375
5	f_2	1.003

Furthermore, the PMP is calculated using Equation 2 and multiplied by a factor of 1.13. The result of PMP in the Logung reservoir basin is 704 mm.

The design rainfall is obtained through the analysis frequency of 40 years of annual maximum rainfall data. The design rainfall is in the return period of 1000 and PMF. The results of the frequency analysis can be seen in Table 4.

Table 4. Design rainfall.

Return period	Rainfall (mm)
1000 year	409
PMP	704

The rainfall pattern was created using the Alternating Block Method (ABM). The rainfall duration approach was carried out using time of concentration. The time of concentration was calculated by the Australian Rainfall-Runoff and Kirpich equations with results of 2.98 and 3.2 hours. The rainfall duration for further analysis is 3 hours, with the river's velocity estimated at two meters per second. The 1000 return rainfall and PMP were designed to be distributed for 3 hours using the ABM method. The design rainfall of 1000-year and PMP presented in Figure 7 and Figure 8.

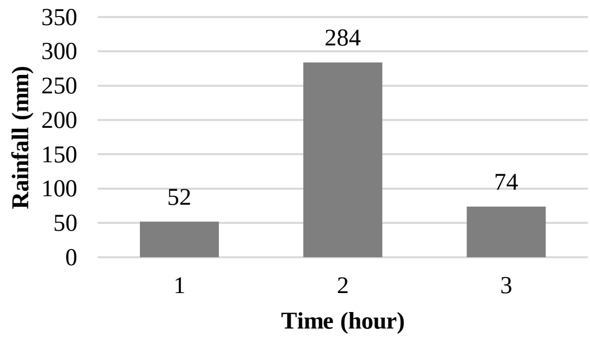

Figure 7. 1000-year rainfall pattern.

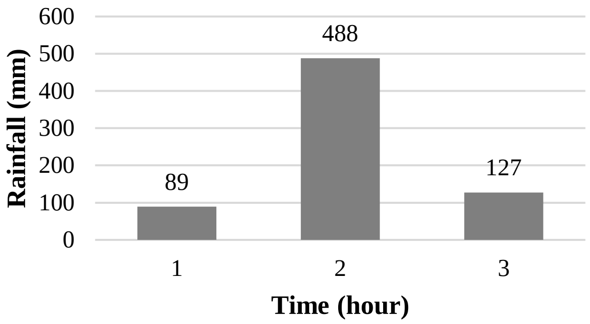

Figure 8. PMP rainfall pattern.

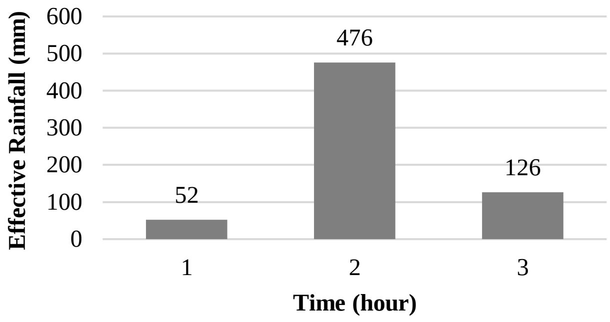

Figure 10. PMP design rainfall

The effective rainfall is calculated using the SCS method [14]. The Curve Number (CN) of the watershed was obtained from the land use map analysis using ArcGIS. The composite CN of the Logung basin can be seen in Table 5. The composite Curve Number of the watershed in the AMC-II condition is 71.40.

Table 5. The composite Curve Number of Logung Basin

Land use	Area (km²)	Weighted area	CN	Weighted CN
Shrubs	2.07	0.04	60	2.62
Forest	3.72	0.08	58	4.56
Residential	5.27	0.11	74	8.23
Meadow	0.00	0.00	73	0.00
Field	1.78	0.04	68	2.56
Rainfed	15.09	0.32	75	23.91
Moor	19.41	0.41	72	29.53
Composite CN				71.40

Most floods occur when the watershed condition is wet. Therefore, the effective rainfall calculation uses CN-III or CN in AMC-III. CN-III is obtained from the CN-II conversion using Equation 10.

$$\text{CN (III)}=\frac{23\ \text{CN(II)}}{10+0{,}13\ \text{CN(II)}}=85.2$$

1000-year and PMP effective rainfall distribution are calculated using CN(III) with Equation 7. The results are presented in Figure 9 and Figure 10.

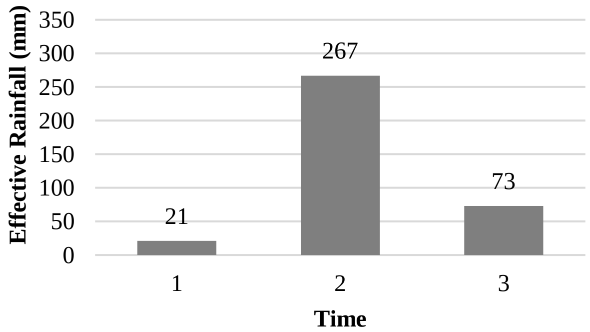

Figure 9. 1000-year design rainfall

For an ungauged catchment such as Logung basin, the unit hydrograph method was applied for the transformation of rainfall-runoff. The unit hydrograph used in this study is Gama-I and Nakayasu. The results of HSS Gama-I parameters are shown in Table 6.

Table 6. Gama-I Unit Hydrograph Parameters

Parameter		
T_R	1.583	hour
Q_p	3.336	m^3/s
T_B	20.99	hour
K	5.261	

From the parameters shown in Table 6, the unit hydrograph is made by calculating the discharge for each time step. The unit hydrograph is the hydrograph produced by the unit time of rainfall. It is necessary to check the runoff volume of 1 mm of rain. The runoff volume is obtained by summing all the unit hydrograph ordinates and multiplying it by the hydrograph time interval. Rainfall depth is calculated by dividing the runoff volume by the watershed's area. The Gama-I UH runoff volume was 20,417 m^3, while the rain depth was 1.678 mm. Because the rain depth is not equal to 1 mm, a correction is made to the unit hydrograph by multiplying the correction factor by f = 1/1.678 = 0.596. The corrected Gama-I unit hydrograph shown in Figure 11.

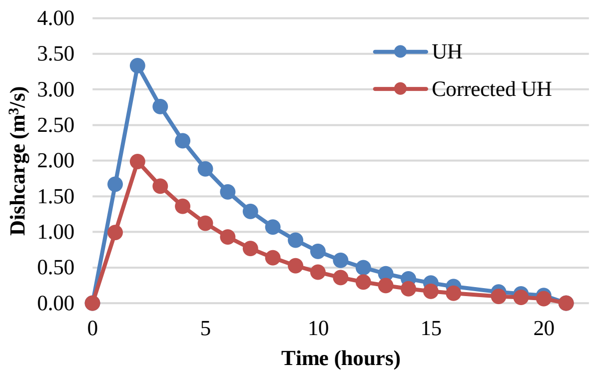

Figure 11. Gama-I unit hydrograph of Logung Basin

Nakayasu unit hydrograph calculation results 22 hours with a peak discharge of 3.34 m^3/s. Nakayasu's UH curve is presented in Figure 12.

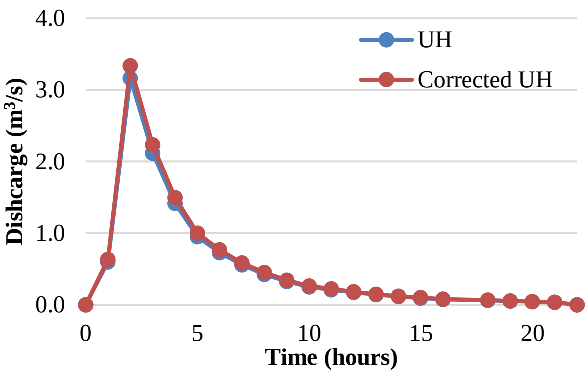

Figure 12. Nakayasu unit hydrograph of Logung Basin

The unit hydrographs of Gama-I and Nakayasu provide different hydrograph curves. The Nakayasu unit hydrograph gives a relatively steep hydrograph shape, while the Gama-I synthetic unit hydrograph is sloping. The peak discharge of the Nakayasu unit hydrograph is much larger than that of Gama-I. A comparison of HSS Gama-I and Nakayasu results is given in Figure 13.

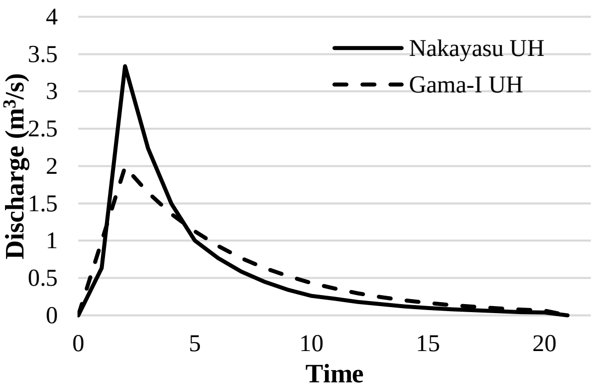

Figure 13. Gama-I and Nakayasu UH comparison

A watershed has a unique rainfall-runoff transformation characteristic. The uncertainty of natural phenomena needs to be simplified. One of the widespread rainfall-runoff transformations is the unit hydrograph method. This method is applied assuming the discharge is directly proportional to the rainfall and the recession time remains constant [13], [14]. The determination of the unit hydrograph method influences the flood discharge design.

The unit hydrographs obtained from the calculations show significant differences between the Nakayasu and Gama-I methods. The time base of the Nakayasu and Gama-I unit hydrographs is not that different, but the peak discharge is very significant (Figure 13). Gama-I is a unit hydrograph method derived from rivers in Java. Therefore, this method should be more suitable for modeling the rainfall-runoff characteristics of the Logung River. Analysis of the 1000-year flood and PMF were derived using the Gama-I unit hydrograph. Baseflow is estimated using the Frequency Discharge Curve method based on streamflow data as Figure 14. The baseflow is set at 50% discharge (Q_{50}) obtained from FDC as Figure 15.

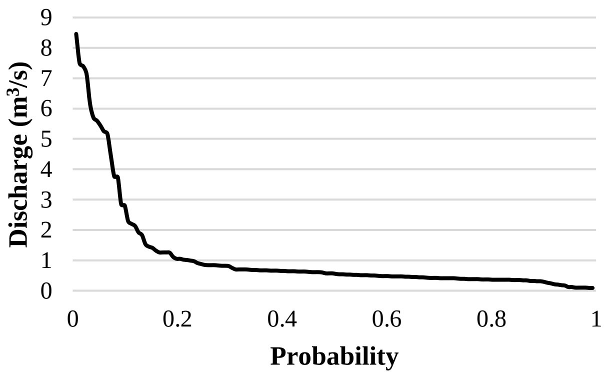

Figure 15. Frequency Discharge Curve of streamflow

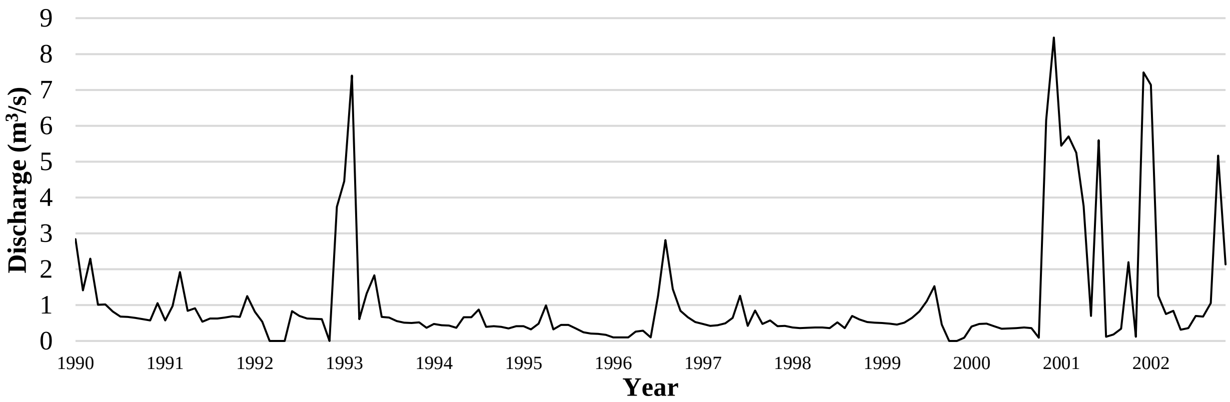

Figure 14. Stream flow data of Logung River for baseflow estimation

Reservoir flood routing analysis

PMF and 1000 years inflow discharge is obtained by multiplying the design rainfall and the synthetic unit hydrograph. PMF and 1000-year inflow hydrographs are shown in Figure 16. The maximum 1000-year flood is 649 m^3/s, and the maximum PMF is 1,168 m^3/s.

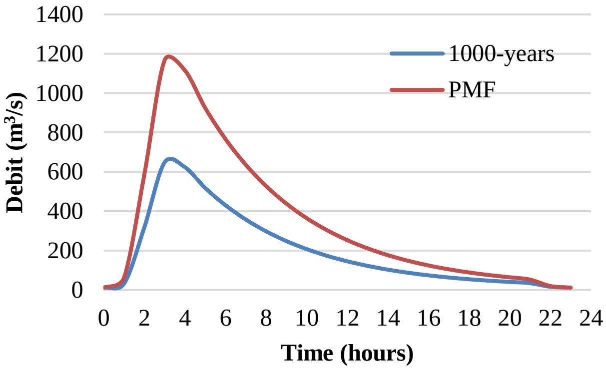

Figure 16. The inflow hydrograph of reservoir

The Logung existing spillway geometri data is a width of 32.4 m, a crest elevation of 88.5 MSL, and a dam elevation of +94 MSL. The discharge coefficient is obtained using the Iwasaki formula of 2.15.

Figure 17 presents a hydrograph of inflow, outflow, and water level from the results of 1000-year flood routing. The maximum inflow is 649 m^3/s, and the maximum outflow is 424 m^3/s. The maximum water elevation of 1000-year floods is +91.8 m. It is known that the dam's top elevation is +94 m, so there is no overtopping. The dumping efficiency value for reservoir routing with the 1000-year flood is 35 %.

Figure 18 presents a hydrograph of inflow, outflow, and water level from the results of PMF flood routing. The maximum inflow is 1,168 m^3/s, and the maximum outflow is 920 m^3/s. The maximum water elevation of PMF floods is +94.1 m. It is known that the dam's top elevation is +94 m resulting in the overtopping of the dam. The dumping efficiency value for reservoir routing with the PMF flood is 21%.

5. Conclusions

A spillway is a dam safety structure. Evaluation of dam spillway performance is needed to determine the potential hazard when extreme flooding occurs. The results of the 1000-year rainfall analysis and PMP for the Logung dam basin were 409 mm and 704 mm, respectively. Rainfall distribution is made using ABM, and effective rainfall is calculated by the SCS method. Land use analysis in the Logung dam watershed obtained a CN-II of 71.4 and a CN-III of 85.2. The rainfall-runoff transformation method used a unit hydrograph. The Nakayasu and Gama-I unit hydrographs show significant differences from the peak discharge, although not for the time base. The 1000-year floods and PMF analysis were derived using the Gama-I hydrograph unit.

The peak discharge for the 1000-year flood and the PMF were 879 m^3/s and 1,168 m^3/s. The flood hydrograph design affects the reservoir performance. The reservoir flood routing results in a dumping efficiency of 35% for the 1000-year and 21% for PMF. The 1000-year flood routing shows that there was no risk of overtopping. The highest water level on the PMF flood routing at +94.1, while the dam's top elevation at +94. Several solutions can prevent overtopping by reducing inflow discharge through small dams upstream, increasing the green area, or modifying spillway structure.

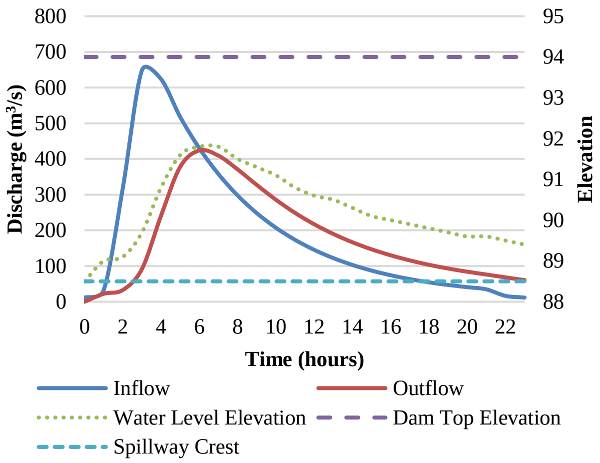

Figure 17. 1000-year flood routing result

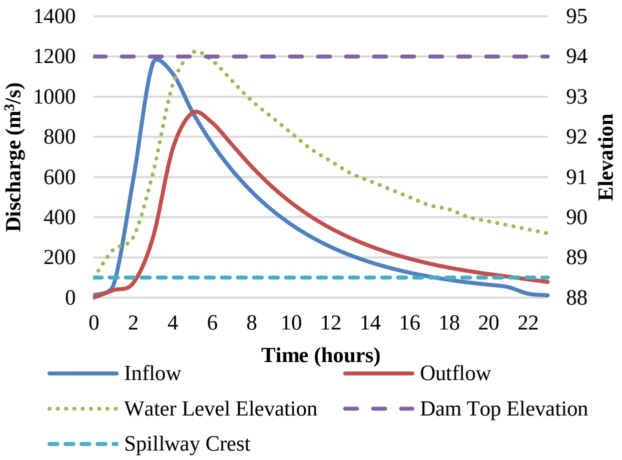

Figure 18. PMF reservoir routing result

References

[1] J. Boulange, N. Hanasaki, D. Yamazaki, and Y. Pokhrel, "Role of dams in reducing global flood exposure under climate change," *Nature Communications 2021 12:1*, vol. 12, no. 1, pp. 1–7, Jan. 2021, doi: 10.1038/s41467-020-20704-0.

[2] I. Khaddor, M. Achab, M. R. Soumali, A. Benjbara, and A. H. Alaoui, "The impact of the construction of a dam on flood management," *Civil Engineering Journal (Iran)*, vol. 7, no. 2, 2021, doi: 10.28991/cej-2021-03091658.

[3] R. Vanijjirattikhan, C. Thongthamchart, P. Rakcheep, U. Supakchukul, and J. Suwatthikul, "Reservoir flood routing simulation for dam safety management in Thailand," *Journal of Disaster Research*, vol. 16, no. 4, 2021, doi: 10.20965/JDR.2021.P0596.

[4] I. A. ' 'Firman, "Tipe Bendungan di Indonesia : Identifikasi dari 130 proyek yang selesai sampai tahun 2010," in *Seminar Nasional Bendungan KNIBB*, 2016.

[5] S. Sosrodarsono, Takeda, and Kensaku, "Bendungan Type Urugan," *Pradnya Paramita*, 1977.

[6] Direktorat Jenderal Sumber Daya Air, *Pedoman Kriteria Umum Desain Bendungan*. Jakarta: Direktorat Jenderal Sumber Daya Air, 2003.

[7] P. Choudhury, R. K. Shrivastava, and S. M. Narulkar, "Flood Routing in River Networks Using Equivalent Muskingum Inflow," *J Hydrol Eng*, vol. 7, no. 6, pp. 413–419, Nov. 2002, doi: 10.1061/(ASCE)1084-0699(2002)7:6(413).

[8] BBWS Pemali Juana, "Sertifikasi Desain Pembangunan Bendungan Logung, Kabupaten Kudus, Jawa Tengah," Jakarta, 2015.

[9] Bambang Triatmodjo, *Hidrologi Terapan* . Yogyakarta: Beta Offset, 2008.

[10] World Meteorological Organization, *Manual on Estimation of Probable Maximum Flood*. Switzerland: WMO, 2009.

[11] Joko Sujono, "Design Unit Hydrograph Theory," in *Yogyakarta: Eleventh Congres of The Asia and Pacific Division of the International Association of Hydraulic Research*, 1998.

[12] Sri Harto B, *Analisis Hidrologi*. Yogyakarta: Nafiri Offset, 2000.

[13] Sri Harto B, *Hidrologi: Teori, Masalah, Penyelesaian*. Nafiri Offset, 2000.

[14] V. te Chow, "Handbook of applied hydrology," *International Association of Scientific Hydrology. Bulletin*, vol. 10, no. 1, 1965, doi: 10.1080/02626666509493376.