

Study on the Capacity of Auxiliary Weir-Type Spillway at Bulango Ulu Dam Gorontalo Province Using Spillway Routing

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Article Information	ABSTRACT
Article History Received : November 09, 2024 Revised : December 02, 2024 Published : January 04, 2025	The spillway on the dam functions as a safeguard against the dangers of flood water, which overflows gradually to prevent overtopping. The estimated design of flood discharge uses the SCS SUH method, while outflow discharge is calculated through spillway routing based on reservoir storage characteristics. The study results show that the maximum flood discharge with a return period of 2 years up to the Probable Maximum Flood (PMF) scenario is 420.26 m³/s to 2,288.05 m³/s respectively. Spillway routing is carried out to drain flood water from the reservoir, with a maximum outflow discharge of 44.4 m³/s to 1,250.5 m³/s, according to the flood return period. This reservoir is able to reduce flooding significantly, with a flood reduction of 89.4% at a return period of 2 years and 45.3% for PMF. The water level at the spillway was measured at various return periods, indicating there was no overtopping until the PMF flood event. Bulango Ulu Dam, which is designed with a top Dam elevation of +105 m, can safely withstand PMF flood discharge.
Keywords: <i>Bulango Ulu Dam; Flood Discharge; Flood routing; Synthetic unit hydrograph; Spillway routing.</i>	

INTRODUCTION

Spillways on dams have an important function as a safeguard that regulates the flow of flood water, thereby preventing overtopping, which can threaten the dam structure. By gradually releasing flood water through the spillway, the dam is able to maintain the stability and safety of the surrounding area. Apart from that, spillway design also considers the reservoir capacity so that the flow of water through the dam remains controlled (Aydin & Ulu, 2023; Lundin et al., 2023; Mantik & Jean Cross Sihombing, 2023; Salmasi & Abraham, 2023; Schleiss et al., 2023; Sukerta et al., 2022; Varçin et al., 2023)

The Bulango Ulu Dam in Gorontalo Province is designed with adequate capacity to deal with extreme flooding, including the Probable Maximum Flood (PMF) scenario. This control capacity allows the reservoir to reduce the volume of outflow, thereby reducing the potential risk of flooding in downstream areas (Acheampong et al., 2023; Auster et al., 2022; Beza et al., 2023; Bigham et al., 2024; Chin et al., 2022; Eldeeb et al., 2023; Gaagai et al., 2022; Ma et al., 2022; Muchlis et al., 2021; Ngo et al., 2016; Saghafian et al., 2014; Stähly et al., 2019; Sun et al., 2023). The spillway on this dam helps drain water efficiently without causing excessive water level rise above the spillway, ensuring the safety of the dam structure and the surrounding area. Safety in dam operation is highly dependent on the spillway's ability to withstand large flood volumes. With

a top dam elevation of +105 m, the Bulango Ulu Dam is designed to control outflow in various extreme flood scenarios.

The Bulango Ulu Dam spillway features a two-elevation system, incorporating a primary and auxiliary weir configuration. This multi-level structure, commonly referred to as a stepped spillway, allows for effective management of flow capacity across different elevation levels, ensuring efficient handling of flood discharge under varying water level scenarios (Chilson & Hudock, 2011a, 2011b; Gessler et al., 2018). In this design, the primary weir, situated at a lower elevation, manages normal flood discharge, allowing water to overflow through it initially. As discharge increases beyond its capacity, the auxiliary weir, positioned at a higher elevation, provides additional protection, particularly during extreme events such as the PMF flood scenario. This dual-level system is especially advantageous for dams with large reservoirs, enabling gradual runoff management and reducing the risk of overtopping.

Therefore, the spillway construction must be designed in such a way that it can channel the designed flood discharge. Based on certain types and specifications, the safety requirement against runoff is that in the design flood discharge conditions, there must be a space with a certain guard height. If the flood discharge conditions for the overflow requirements are not met, the spillway capacity will not be sufficient to allow the outflow of water, thereby endangering the dam construction. For the reasons mentioned above, it is necessary to carry out hydrological and hydraulic studies on a dam in the form of routing the flow through the spillway and to achieve the objectives of this research using the SCS Synthetic Unit Hydrograph (SUH) method (Natakusumah et al., 2011) to calculate the designed flood discharge and spillway routing analysis using methods based on the characteristic capacity of the reservoir storage and spillway design.

RESEARCH METHODS

This study focuses on spillway routing for the Bulango Ulu Dam, located in Gorontalo Province, within the 243.19 km² Bulango Ulu watershed (DAS). The Mongilo River, which spans 27.59 km, serves as the primary river system with five hierarchical orders of streams. The dam's overflow system is designed as an Auxiliary Weir with an arc-shaped configuration and two distinct elevation levels. These elevation differences aim to manage small flood discharges below the 100-year return period more effectively. The normal water level is set at +95.00 with a service overflow width of 8 m, while the secondary level, or SWL, is at +97.5 with an auxiliary width of 28 m. Upstream, the overflow structure employs a broad-crested threshold, transitioning downstream to a slope of 1:0.25. The methodology in this study involves several key stages, including rainfall data collection, rainfall analysis design, design flood discharge calculation, and flood routing analysis. The following outlines the steps undertaken in the research process:

Rainfall Data Collection

The rainfall data used is the result of recording from the station closest to the location of the Bulango Ulu Dam in the Bulango watershed, namely at Dulamayo Rainfall Station. The rainfall data that has been collected is daily rainfall data for 15 years (2007 - 2021) and maximum daily rainfall data (2007 - 2021). The available rainfall data, the use of the data is adjusted to hydrological analysis by checking the absence of trends in the data range using Spearman's Rank-Correlation Method and checking the consistency of the data using the RAPS (Rescaled Adjusted Partial Sums) Method.

Calculation of Design Rainfall and Design Flood Discharge

The next stage in this research is to carry out rainfall frequency analysis to obtain design rainfall with various return periods. For analysis purposes, rainfall is determined with return periods of 2, 5, 25, 50, 100, 1000 years, and PMP. In this study, the designed rainfall analysis will be carried out using the Gumbel method, Pearson Log Type III, and Normal and Normal Log. Determine which method can be applied; it will be selected after testing the level of suitability. After obtaining the design rainfall, the next stage is to calculate the percentage intensity of the hourly rain distribution in the Bulango Ulu watershed based on the runoff coefficient from the land use of the Bulango Ulu watershed.

The unit hydrograph is used to determine the design of flood discharge, considering that there is no flood discharge data available in the field. More specifically, if in an unmeasured watershed (AWLR data is not available), then the unit hydrograph is derived using a synthetic method or, better known as a Synthetic Unit Hydrograph (SUH) by calculating the main elements of the unit hydrograph (Q_p , T_p , and T_b) as a function of watershed characteristics. In this study, the Synthetic Unit Hydrograph (SUH) method employed is the Soil Conservation Service (SCS) SUH. This method is chosen due to its simplicity and flexibility in standardizing the time interval for routing calculations across multiple sub-watersheds. The SCS SUH is particularly advantageous in areas with limited hydrological data, as it relies on widely available parameters such as rainfall intensity, curve numbers, and watershed characteristics, making it highly adaptable for diverse hydrological conditions. Additionally, the SCS SUH offers a systematic approach for modeling runoff responses, ensuring consistency in hydrograph generation across sub-watersheds. This consistency facilitates accurate routing analysis, particularly in studies involving complex watershed systems. The equation and graphical representation of the SCS SUH are provided in the following sections.

$$Q_p = C \frac{A}{T_p} \quad (1)$$

$$T_{lag} = 0.6 T_{lag} \quad (2)$$

$$T_p = \frac{D}{2} + T_{lag} \quad (3)$$

Where :

Q_p = peak discharge (m^3/s)

A = watershed area (Km^2)

T_p = time from the start of the flood to the peak of the flood hydrograph (Hour)

Equation Modeling of Reservoir Storage Characteristics

The storage characteristics of the Bulango Ulu reservoir studied include a total inundation area of 633 Ha, with a minimum bed elevation of +81.00 m and a dam peak elevation of +105.00 m. The designed spillway peak elevation is set at +95.00 m and +97.50 m, which results in a storage volume capacity for the Q_{PMF} flood capacity of $132.32 \times 10^6 \text{ m}^3$.

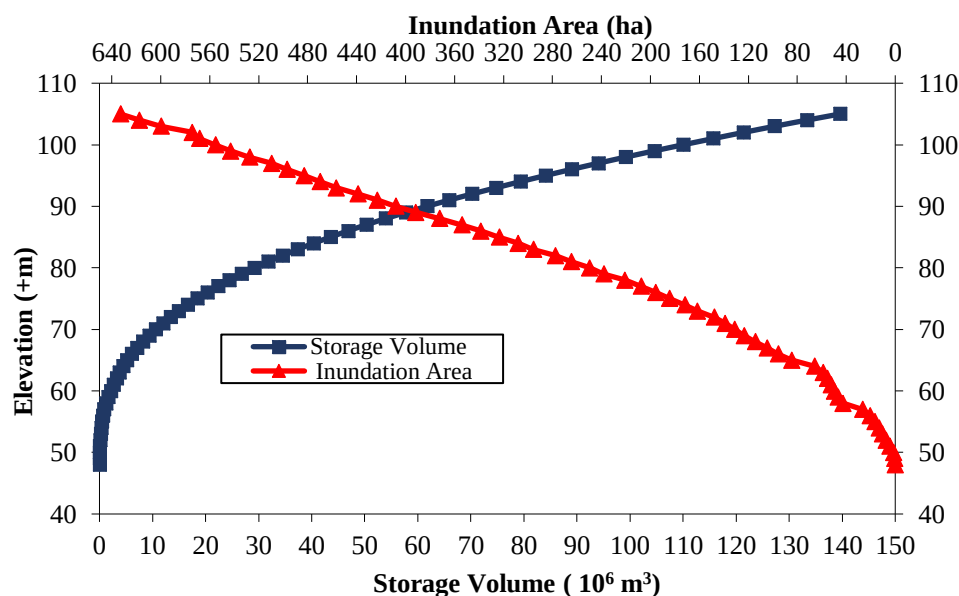


Figure 1. Characteristics of the Bulango Ulu reservoir storage in Gorontalo Province

Based on data on reservoir storage characteristics shown in Figure 1, a mathematical relationship (regression method) has been developed between elevation and reservoir storage volume, which produces Equations (4) and (5). These relationships are an important basis for further analysis regarding spillway routing calculations to maximize storage capacity and prevent the risk of overtopping.

$$S = 0.0035 \cdot (H - 47)^{2.6019} \quad (4)$$

$$H = 47 + \text{Exp}(\ln(\frac{S}{0.0035})/2.6019) \quad (5)$$

Where :

S = Storage (MCM)

H = elevation (m)

Spillway Routing

After the stage of the designed flood discharge is obtained, the next stage is to carry out flood routing to model the water flow through the spillway in the reservoir storage system. Flood routing is carried out using the Bulango Ulu Reservoir storage volume characteristic method, as shown in Figure 1. This method was chosen because of its accuracy in solving non-linear equations, which are often found in routing flow through spillways. Through this investigation, it is possible to determine the response of the spillway system to inflow flood discharge, including the water level in the reservoir and the outflow through the spillway.

Flood routing in reservoirs is needed to obtain data on maximum outflow discharge and maximum water level elevation in the reservoir. Flood routing analysis is used to design whether the 1000-year return period flood discharge (Q_{1000}) and Q_{PMF} entering the Bulango Ulu reservoir cause water overflow. If no overflow occurs, then the simulation of reservoir embankment failure is assumed to occur due to seepage. Flood routing analysis equation using Equation (6):

$$I - O = \frac{dS}{dt} \quad (6)$$

The equation for calculating flood routing in reservoirs uses Equation (7):

$$S_{j+1} - S_j = \left((I_j + I_{j+1})\Delta t - \left(\frac{Q_j + Q_{j+1}}{2} \right) \Delta t \right) \quad (7)$$

where: I = Inflow hydrograph, O = Outflow hydrograph, S = Storage function, Δt = Duration interval

The relationship curve between water level elevation and discharge when passing through the spillway is determined from the hydraulic equation as follows:

$$Q = C B H^{3/2} \quad (8)$$

Where: Q = discharge (m^3/s), C = spillway coefficient (1.3 ~ 2.2), B = spillway width (m), H = water level above the spillway (m).

RESULTS AND DISCUSSION

Design of Rainfall and Flood Discharge

Design rainfall calculations for various return periods can be calculated using frequency analysis based on annual maximum daily rainfall data. In this research, the analysis was carried out using four distributions, namely Gumbel, Log Normal 2 Parameters, Log Pearson III, and Normal. The analysis obtained was to determine the Log Pearson III method as the distribution method that will be used in subsequent hydrological analysis. This selection was based on the error value from the Chi-Square and Smirnov Kolmogorov test results, which had the smallest results

compared to the other values. Based on the feasibility test, the Log Pearson III distribution meets the requirements. Figure 2 shows the results of the analysis namely the frequency of rain at a return period of 1.01 years is 44.58 mm, a return period of 2 years is 79.25 mm, a return period of 5 years is 101.20 mm, a return period of 10 years is 115.93 mm, the 20 year return period is 130.26 mm, the 25 year return period is 134.86 mm, the 50 year return period is 149.21 mm, 100 year return period of 163.81 mm, 200 year return period of 178.78 mm, 1000 year return period of 215.37 mm, and PMP of 431.46 mm.

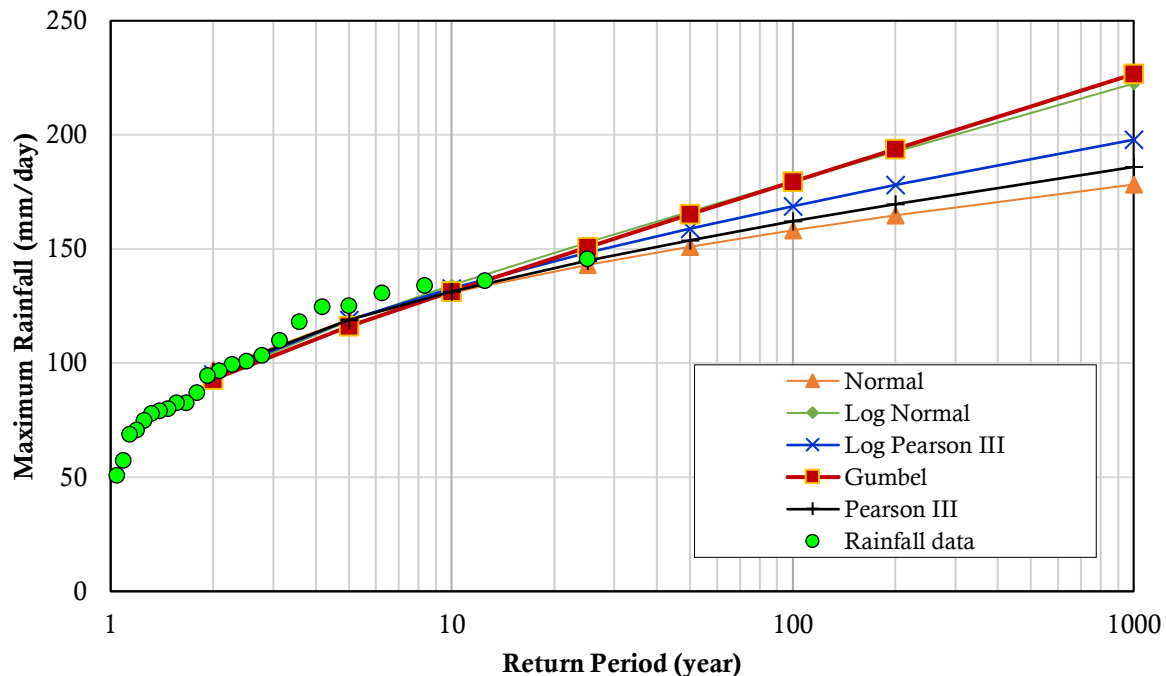


Figure 2. Rainfall plotting of various return periods

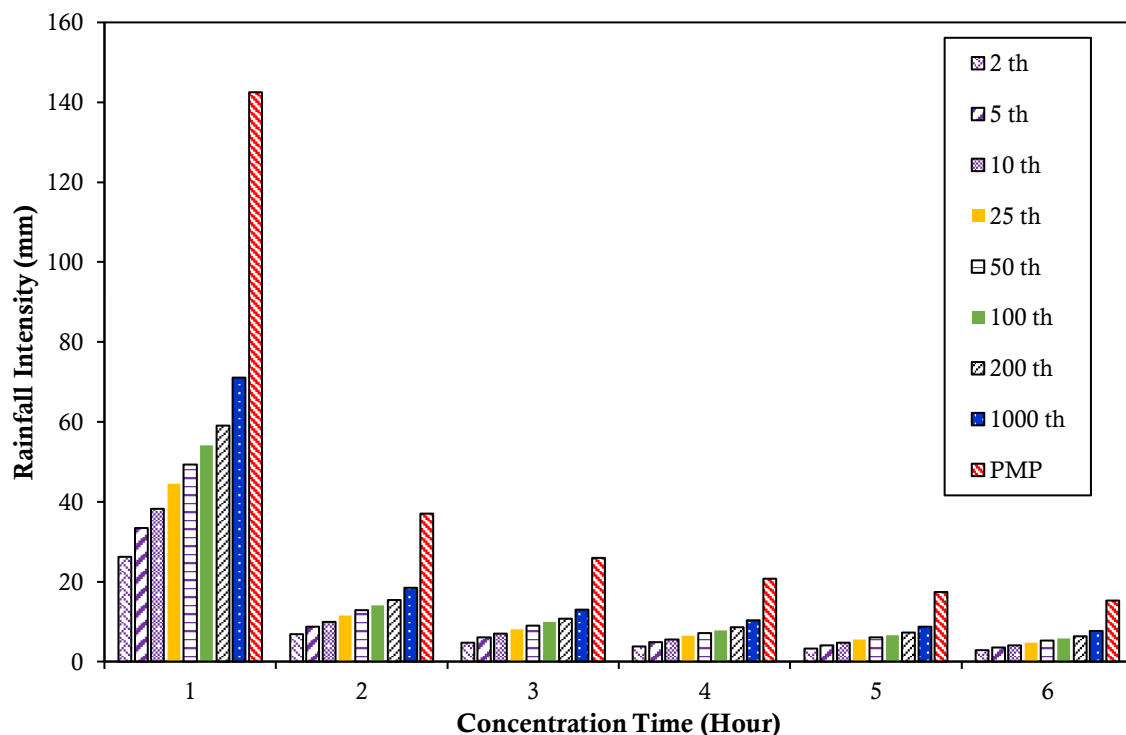


Figure 3. Hourly rainfall distribution

The results of the design rainfall analysis using the Log Pearson Type III method are daily design rainfall, and the design rainfall must be transformed into effective rainfall or hourly rainfall distribution; for in Indonesia, various literature states that the transformation of hourly rainfall distribution is distributed over 6 hours. Figure 3 shows the results of the analysis of the distribution of hourly rainfall at various return periods. The distribution of hourly rainfall for the PMP return period for 6 consecutive hours, namely the first hour was 142.46 mm, the second hour was 37.03 mm, the third hour was 25.98 mm, the fourth hour was 20.68 mm, the fifth hour was 17.46 mm and the sixth hour was 15.26 mm. The distribution of rainfall during these periods will be a multiplying factor to determine the flood design for various return periods in the analysis of the spillway routing of the Bulango Ulu Dam in Gorontalo Province.

The next analysis is calculating the design flood discharge using the SUH SCS method. Before obtaining the design flood discharge caused by effective rain, first calculate the SUH or peak discharge caused by effective rainfall of 1 mm. The results of the SUH SCS analysis in the Bulango Ulu watershed showed that the flood discharge caused by 1 mm of effective rain was 1.1378 m³/s with a peak time of 2 hours. The next stage is to calculate the design flood discharge resulting from effective rainfall (hourly rainfall distribution) at various return periods, which was analyzed in the previous stage. The following is a recapitulation of the results of flood discharge calculations designed for various return periods in the Bulango Ulu watershed in Gorontalo Province. This analysis also considers the calculation of the flood discharge for the Bulango Ulu watershed, calculated per each sub-watershed, to examine in detail the flood routing from another sub-watershed to another sub-watershed until it reaches the outlet point or sub-watershed outlets in assessing flood discharge per sub-watershed, the SUH used uses the SUH SCS method to make it easier to equate hydrograph interval times in all sub-watersheds for future flood routing needs. The following is the flood discharge per sub-watershed for each with a return period of 1000 years. The PMF can be seen in Table 1 and Figure 4 below.

Table 1. Recapitulation of the 1000-Year Return Flood Discharge and PMF for Each Bulango Sub-Watershed

No	Subbasin	Areas (Km ²)	River Length (Km)	River Slope (-)	Q_{1000} Years (m ³ /s)	Q_{PMF} (m ³ /s)
1	Sub Outlet	21.04	11.19	0.04	127.50	255.42
2	1A	12.72	8.99	0.06	88.47	177.23
3	1B	16.29	9.42	0.04	109.15	218.67
4	2A	15.44	10.44	0.09	105.85	212.05
5	2B	21.32	9.62	0.08	149.29	299.07
6	3A	0.14	0.92	0.31	2.28	4.56
7	3B	17.08	9.85	0.13	120.18	240.77
8	4A	11.96	8.18	0.12	95.37	191.06
9	4B	16.79	8.3	0.1	132.76	265.95
10	5A	2.32	4.16	0.14	20.76	41.58
11	5B	18.55	10.51	0.07	125.09	250.60
12	6A	14.14	8.07	0.18	122.38	245.17
13	6B	6.61	4.83	0.27	64.61	129.44
14	7A	28.14	11.94	0.09	187.03	374.69
15	7B	18.9	9.69	0.15	140.36	281.18
16	8A	15.81	8.55	0.14	127.65	255.71
17	8B	7.34	4.83	0.26	72.02	144.29



Figure 4. Flood discharge map for each sub-watershed for the 1000-year return period and PMF

From Table 1 and Figure 4, it can be seen that the largest flood discharge occurred in sub-watershed 7A, with a maximum flood discharge during the 1000-year return period of $187.03 \text{ m}^3/\text{s}$ and the PMF return period with a maximum flood discharge of $374.69 \text{ m}^3/\text{s}$. For the next stage, flood routing analysis is carried out in each sub-watershed to obtain the total flood discharge that passes through the control points in the outlet sub-watershed sections. Based on the basic concept of flood routing theory in each sub-watershed, the analysis uses the Muskingum routing method for rivers. In contrast, spillway routing uses a concept based on reservoir storage capacity

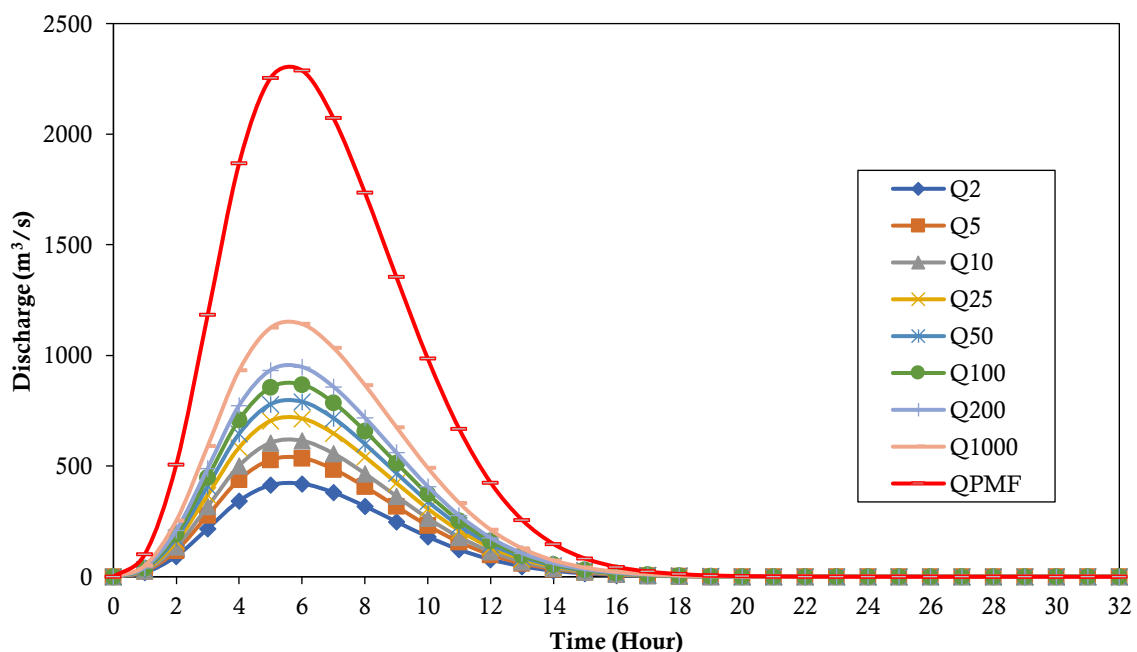


Figure 5. Total Flood Discharge (Outflow at Outlet Section) Routing Results Per Sub-Watershed

Spillway Routing Analysis

The results of the spillway routing analysis during flood events in the Bulango Ulu watershed were carried out based on the storage capacity of the Bulango Ulu Reservoir without considering the use of circumvention tunnels. From the calculation results, the maximum outflow discharge value produced by flood discharge for various return periods is obtained. At the 2-year return period, the maximum outflow discharge reaches $44.4 \text{ m}^3/\text{s}$, where the spillway crest Auxiliary Weir is not used. At the 5-year return period, the maximum outflow discharge is $62.4 \text{ m}^3/\text{s}$, with spillway crest Auxiliary Weir operating for 1 hour. For the 10-year return period, the maximum outflow discharge increases to $272.5 \text{ m}^3/\text{s}$, and the spillway crest Auxiliary Weir is used for 3 hours. At the 25-year return period, the maximum outflow discharge was recorded at $314.9 \text{ m}^3/\text{s}$ with the use of spillway crest Auxiliary Weir for 5 hours, while at the 50-year return period, the outflow discharge reached $359.7 \text{ m}^3/\text{s}$, with the duration of operation of spillway crest Auxiliary Weir for 7 hours.

For the 100-year return period, the maximum outflow discharge was recorded at $390.5 \text{ m}^3/\text{s}$ with the duration of use of spillway crest Auxiliary Weir for 9 hours, while at a return period of 200 years, the maximum outflow discharge increased to $436.8 \text{ m}^3/\text{s}$, and spillway crest Auxiliary Weir is used for 10 hours. At the return period of 1000 years, the outflow discharge reaches $540.8 \text{ m}^3/\text{s}$, with the use of a spillway crest Auxiliary Weir for 12 hours. As for the Probable Maximum Flood (PMF) scenario, the maximum outflow discharge reaches $1,250.5 \text{ m}^3/\text{s}$ (see Figure 6), with the spillway crest Auxiliary Weir operating for 17 hours.

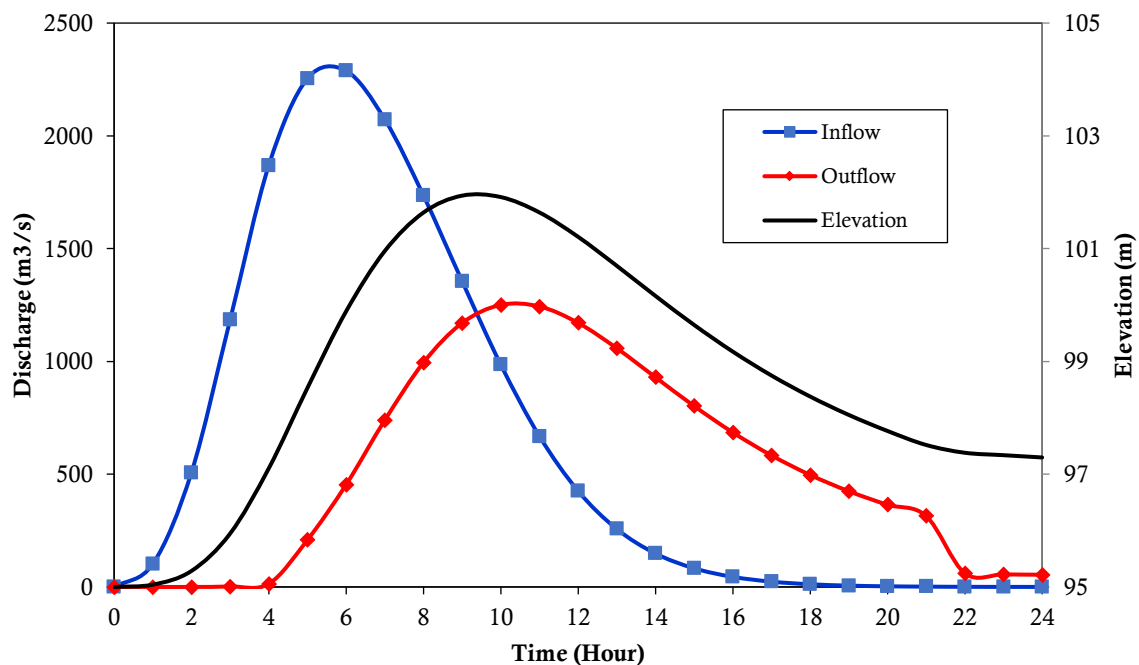


Figure 6. Hydrograph of PMF Flood Spillway Discharge from Bulango Ulu Dam

Based on the analysis results shown in Figure 7, the maximum reservoir elevation during the PMF flood was still below the Top Dam elevation at +105 m, with a guard height of 3.06 m from the spillway, so that overtopping did not occur. However, due to the water level elevation when the PMF approaches the Top Dam with a difference of around 3.06 m, the dam is considered to be in alert status. In this situation, reservoir operators need to prepare alternatives for discharging flood discharge, for example, by opening the bypass outlet door or using other available outlets to prevent further risks.

The results of other spillway routing analyses in the Bulango Ulu watershed, shown in Figure 7, show an increase in reservoir water level based on various flood return periods. At the 2-year return period, the water level of the type $L = 8 \text{ m}$ spillway reaches 2.04 m. For a return period

of 5 years, the water level reaches 2.56 m on the $L = 8$ m type spillway and 0.06 m on the $L = 28$ m type; the 10-year return period reaches 2.51 m (L type = 8 m) and 0.01 m (L type = 28 m). At the 25-year return period, the estimated water level is 2.77 m (type $L = 8$ m) and 0.27 m (type $L = 28$ m); the 50-year return period reaches 3.02 m (L type = 8 m) and 0.52 m (L type = 28 m); up to a return period of 1000 years with an estimated water level of 3.97 m (type $L = 8$ m) and 1.47 m (type $L = 28$ m). During the PMF return period, the maximum water level reaches 6.94 m for the $L = 8$ m type and 4.44 m for the $L = 28$ m type, while the maximum reservoir water level reaches +101.94 m.

Apart from that, the Bulango Ulu Reservoir has a significant ability to reduce flooding in the downstream area of the Mongilo River thanks to a storage system that is effective in reducing runoff at various return periods. During the 2-year return period, this reservoir was able to reduce flooding by up to 89.4%. For the 5-year return period, flood reduction reached 88.4%, while at the 10-year return period, the reduction rate was recorded at 55.7%. At a return period of 25 years, flooding can be reduced by 56.0%, and for a return period of 50 years, the reduction reaches 54.5%. At the 100-year return period, the reservoir succeeded in reducing flooding by 55.0%, while at the 200-year and 1000-year return periods, the reduction rates were 53.9% and 52.6%, respectively. In the Probable Maximum Flood (PMF) flood scenario, this reservoir is able to reduce flooding by 45.3%. These results confirm the effectiveness of the Bulango Ulu Reservoir in controlling runoff discharge resulting from extreme flood events, as well as its contribution to reducing the risk of flooding in downstream areas.

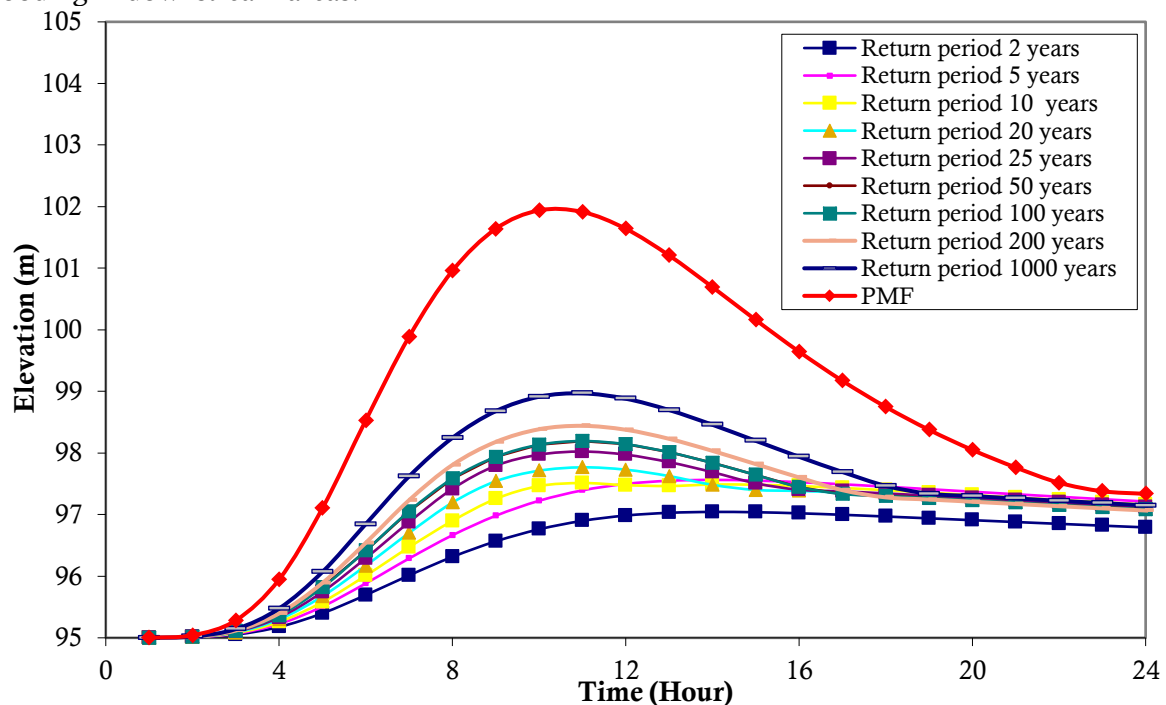


Figure 9. Hourly increase in reservoir water level, results of analysis of spillway routing at various return periods at Bulango Ulu Dam

CONCLUSION

The conclusions obtained from the design flood analysis in the Bulango Ulu watershed show that the maximum discharge with a return period of 2 years has a PMF of 420.26 m³/s to 2,288.05 m³/s, respectively. Spillway routing is carried out to drain flood water from the reservoir, with a maximum outflow discharge of 44.4 m³/s to 1,250.5 m³/s, according to the flood return period. This reservoir is able to reduce flooding significantly, with a flood reduction of 89.4% at a

return period of 2 years and 45.3% for PMF. The water level at the spillway was measured at various return periods, indicating there was no overtopping until the PMF flood event. The Bulango Ulu Dam, which was designed with a Top Dam elevation of +105 m, means that it can be concluded that the capacity of the Auxiliary Weir type spillway at the Bulango Ulu Dam in Gorontalo Province can safely withstand PMF flood discharge.

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