International Journal of Civil Engineering and Infrastructure
Vol. 4, No. 1, March 2024

HYDRAULIC DESIGN OF SMALL EARTH CASCADE DAM FOR DRYLAND GOGO RICE PLANTATION

Wahyu Gendam Prakoso[1], Pengki Irawan[2]
[1]Civil Engineering Department, Faculty of Engineering, Pakuan University, Bogor, Indonesia
Correspondence email: wahyugendamprakoso@unpak.ac.id
[2]Civil Engineering Department, Faculty of Engineering, Siliwangi University, Tasikmalaya, Indonesia
Email: irawan@unsil.ac.id

Received October 13, 2023 | Accepted November 18, 2023

ABSTRACT

The irrigation of gogo rice plantataion on dryland is not extensively developed in Indonesia. Design for the earthfill dam using a combination of hydrological analysis and open-channel hydraulic modeling. Hydrological modeling is conducted by transforming rainfall into runoff using the rainfall- run off model. The hydraulic design involves determining the capacity of the earthfill dam. Hydraulic models and simulations help estimate the potential inflow rates and assess the dam's ability to handle peak flows during extreme weather events. Spillway dimensions are determined based on the dam's design flood criteria, hydraulic modeling, and safety standards. The design of small-scale earthfill dams in cascade to meet the irrigation water needs for dryland paddy plantations in West Tulang Bawang, Lampung, consists of 2 dams (Dam 1: upstream; Dam 2: downstream). Dam 1 effective reservoir 74039 m^3, and the inundation area reaches 10846 m^2. The inflow discharge is 7.3 m^3/second. Total storage volume dam 2 reaching 77023 m^3, and the inundation area is 22000 m^2. The inflow discharge is 14.18 m^3/second. To ensure dam safety, a spillway is designed with an ogee crest using a square-section control with effective widths of 3.0 m for Dam 1 and 4.5 m for Dam 2. Flood reduction in the downstream part of Dam 2 reaches 22% with 10.99 14.18 m3/second outflow discharge and is estimated to be safe to prevent failure due to overtopping hazards. Further research is needed for extreme emergency action plans with simultaneous dam failure scenarios.

Keywords: *Small Earth Dam Design, Cascade Dam, Hydraulic Design, Dryland Irrigation, Gogo Rice Plantation*

1. PRELIMINARY

Earthfill dams represent a remarkable feat of engineering, designed to withstand immense pressure and control the flow of water for various purposes such as irrigation, flood control, and hydroelectric power generation. However, behind their imposing structures lies a complex system of hydrology and hydraulics that demands meticulous study and analysis. Hydraulic studies, therefore, emerge as a crucial aspect in the design process of earthfill dams, offering insights into the behavior of water and ensuring the safety and efficiency of these structures.

Hydraulic studies play a fundamental role in the design of spillways and outlet structures, which are vital components for controlling water discharge and maintaining reservoir levels within safe limits. Through hydraulic modeling and simulation techniques, engineers can assess different hydraulic configurations and identify potential bottlenecks or areas of concern. By optimizing the design of spillways and outlets, they can ensure efficient water management while minimizing the risk of erosion, scouring, or structural damage [1]

The irrigation of gogo rice plantataion on dryland is not extensively developed in Indonesia. This research is conducted at PT. Huma Indah Mekar located in Penumangan, West Tulang Bawang Subdistrict, Lampung Province. It is for the development of extensive scale paddy rice food estate. The land includes dryland areas with limited water availability, and the water needs are expected to be met by constructing an earthfill dam to maximize the capacity of the natural reservoirs located at the dryland food estate site.

Figure 1. Small Earth Dam Location on PT. Huma Indah Mekar Gogo Rice Dryland Plantation [2].

2. RESEARCH METHOD

Design for the earthfill dam using a combination of hydrological analysis and open-channel hydraulic modeling. Hydrological modeling is conducted by transforming rainfall into runoff using the rainfall- run off model. The first aspect of hydraulic design involves determining the capacity of the earthfill dam. Capacity refers to the maximum amount of water the dam can impound without compromising its structural integrity or causing overflow. capacity calculation will be based on several factors such as the catchment area, expected inflow, and desired flood protection level. Hydraulic models and simulations help estimate the potential inflow rates and assess the dam's ability to handle peak flows during extreme weather events. Spillway dimensions are determined based on the dam's design flood criteria, hydraulic modeling, and safety standards.

The data required to complete the design of the dam include:

1. Topograpical data; based on terrestrial land survey using Total Station provided by Kaliandra Lestari and PT. Huma Indah Mekar
2. Daily Rainfall Data: Calculations are performed for average rainfall in the area, maximum daily rainfall, rainfall intensity, and the selection of intensity formulas and methods.
3. Existing River Data: long section of the river and cross-sectional profiles of the river channel to obtain the necessary data for this planning report. Additionally, observations are made regarding the available water discharge in the river.

3. DESCRIPTION AND TECHNICAL

In river planning, to estimate the design flood hydrograph using the unit hydrograph method, it is necessary to first determine the temporal distribution of rainfall with a specific interval. Since hourly rainfall data is not available, Mononobe method is used for rainfall distribution, assuming the duration of rainfall in the study area [3].

Rainfall-runoff transformation is a process of converting rainfall into actual flow; rainfall flows from upstream to downstream until the control point as surface runoff, eventually becoming runoff. In this transformation process, a rule (regulation/model) reflecting the watershed characteristics is needed to understand the conversion of rainfall into runoff using (SWMM) Storm Water

Management Model software. Area of Interest (AOI) parameters, land cover, streamflow, and others based on field observations and Geographic Information System (GIS) analysis [3].

Rain intensity is the height or depth of rainfall per unit of time. A common characteristic of rainfall is that the shorter the duration of rainfall, the higher the intensity tends to be, and the longer the return period, the higher the intensity as well. Analysis of rainfall intensity can be processed from rainfall data that has occurred in the past. Formulas that can be used:

According to Dr. Mononobe, if the available rainfall data is only daily rainfall [3][5]. The formula used as follows :

$$I = \frac{R_{24}}{24}\left(\frac{24}{t}\right)^{\frac{2}{3}} \quad (1)$$

Where: I = rainfall intensity (mm/hour), t = duration of rainfall (hours), R24 = maximum daily rainfall (mm).

The calculation of dam capacity follows the general reservoir equation [1], which is a function between area and elevation. The analysis of reservoir capacity and the area of inundation of the dam utilizes the following equation:

$$V_n = \frac{1}{3}\cdot \Delta h\left(F_{n-1} + F_n + \sqrt{F_{n-1}\cdot F_n}\right) \quad (2)$$

Where h is the elevation of each contour, F is the area of the contour. Contours are obtained from terrestrial topographic measurements using a total station, then analyzed using GIS software to obtain the area of each contour. From this data, the storage volume bounded by each contour is obtained, and ultimately, the cumulative storage volume of the dam is determined.

The calculation of spillway capacity is conducted to ensure dam safety from the overtopping risk using hydraulic analysis for the spillway structure according to irrigation planning criteria [3][5][6]

The spillway discharge is calculated using the discharge equation for spillways with a circular crest and rectangular control section.

$$Q_d = C_d x \frac{2}{3} b_{eff} x \sqrt{\frac{2}{3} g x H^{\frac{3}{2}}} \quad (3)$$

Where Q_d is the discharge (m^3/second), Cd is the discharge coefficient, b_{eff} is the effective width of the crest (m), g is the gravitational acceleration, and H is the energy head above the crest (m).

After obtaining flood discharge hydrograph data and the storage function against elevation at the dam, flood routing can be performed at dam. Flood routing is conducted using the Muskingum's method. The equation used in this method is as follows:

$$\frac{2S_{j+1}}{\Delta t} + Q_{j+1} = I_{j+1} + I_j + \frac{2S_j}{\Delta t} - Q_j \quad (4)$$

$$\left(\frac{2S_2}{\Delta t} + Q_2\right) = \left(I_2 + I_1\right) + \left(\frac{2S_1}{\Delta t} - Q_1\right) \quad (5)$$

S is the storage function of the reservoir elevation, Q is the function of spillway discharge, and I is the function of inflow obtained from the flood hydrograph.

The backwater curve is the line representing the rise in water surface upstream of the dam due to impoundment. The influence of backwater is calculated to determine whether the river upstream of the dam requires an increase in embankment height to prevent river overflow. Accurate calculation for the backwater curve can be done using the standard step method if the cross-sections, slopes, and river hardness factors upstream of the dam location are known up to a sufficient distance [5][6][7].

4. RESULT AND DISCUSSION

The rainfall data used in this study consists of rainfall and discharge observation data from Rainfall Stations (PCH), including the North Lampung Climatology Station, Pasawaran, and Radin Intan II.

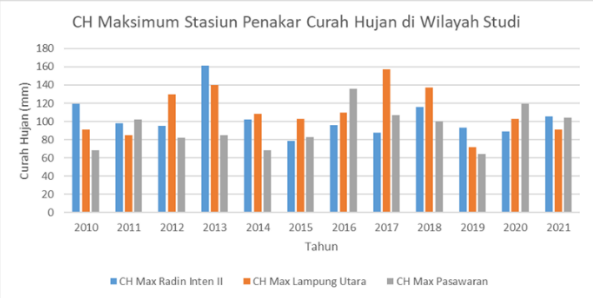

Figure 2. Maximum Daily Rainfall Data from Radin Inten II, Pasawaran, and North Lampung Station 2010 - 2021[8]

To ensure the reliability and accuracy of the analysis or predictions made using the rainfall data, consistency testing is conducted using the double mass curve.

Rainfall calculation in this study employs the Thiessen Polygon method. This method is used to calculate the weight of each station representing its surrounding area. Based on the rainfall analysis using the Thiessen polygon, it was found that the Pasawaran rainfall station is the only influential rainfall station in the area.

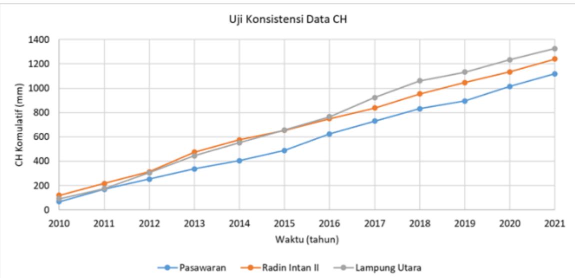

Figure 3. The double mass curve for Rainfall Data Consistency testing

Frequency distribution analysis is intended to obtain the design rainfall magnitude determined based on specific design standards. For analysis purposes, rainfall magnitudes are determined with return periods of 2, 5, 10, 25, 50, 100 up to 1000 years.

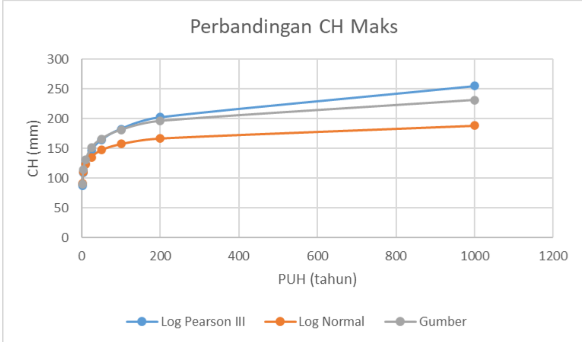

Figure 4. Comparison of maximum rainfall for various rainfall return periods using several rainfall data distributions

Longest Rainfall duration in the Indonesian usually occurs for 6 – 8 hours; therefore, a rainfall model for such duration is necessary. This study utilized an 8-hour rainfall period. The rainfall hydrograph model as shown in Figure 5.

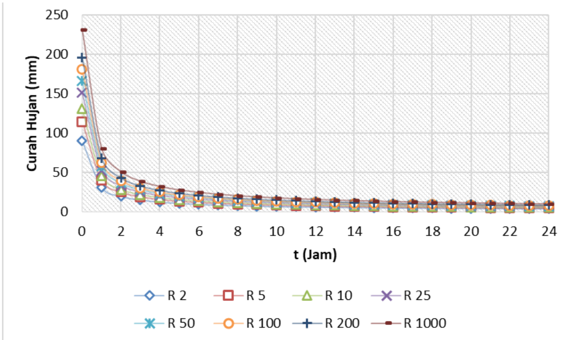

Figure 5. Intensity Duration Frequency Curve.

Runoff analysis is conducted using the Storm Water Management Model (SWMM) software. The parameters include Watershed Area, land cover, streamflow. These parameters are based on field observations and mapping analysis using geographic information systems.

The area of the catchment area for Dam 1 reaches 22.95 hectares, with an average land slope of 11%, a perimeter of the water body holding runoff of 882 meters (contour perimeter 22.5 meters above sea level), impervious area percentage is 95% (during land processing), the land roughness value is 0.4 (grassland). The Rainfall Return Period used is 100 years and simulated in a short duration rain, namely 6 hours.

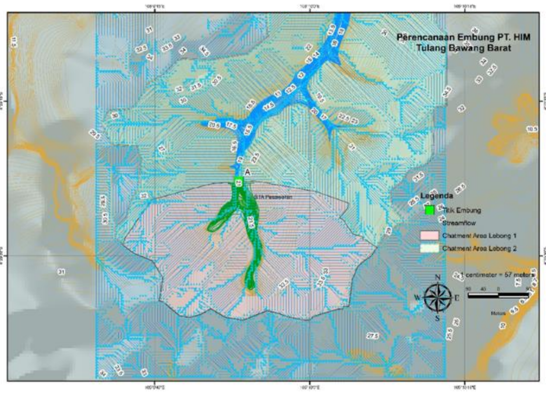

Figure 6. Catchment Area for Dam 1 and Dam 2.

The simulation shows that the maximum runoff discharge that occurs is 7.30 m^3/second with the peak time in the second hour of the simulation. The simulation duration is conducted every 15 minutes to examine the detailed simulation results. The simulation results are presented in the runoff hydrograph shown in Figure 7.

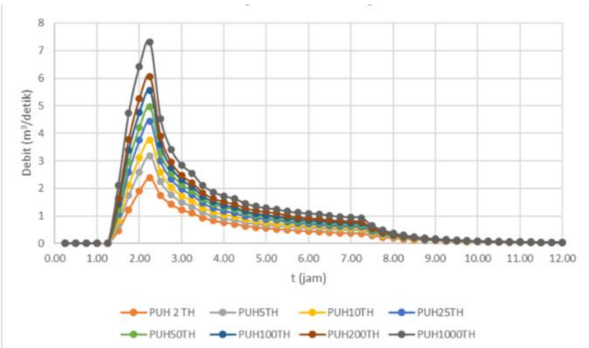

Figure 7. Runoff Hydrograph for Dam 1.

The effective reservoir storage volume is at elevation 22.5 meters above sea level with a total storage volume of 74039 m^3, and the inundation area reaches 10846 m^2. The storage capacity curve will determine the normal water level height at spillway 1, which is at elevation 22.5 meters above sea level. The storage capacity curve and the inundation area of dam 1 can be seen in Figure 8.

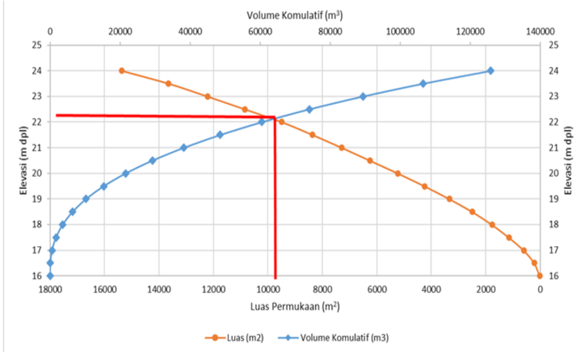

Figure 8. Volume – Area Curve for Dam 1.

The spillway is designed using an ogee-shaped weir with a square-section control with an effective width of 3.0 meters. The spillway capacity curve can be seen in Figure 9.

The flood reduction calculation for dam 1 is performed using the Muskingum method. The maximum inflow is 7.3 m3/second, while the outflow through the spillway is only 1.23 m3/second.

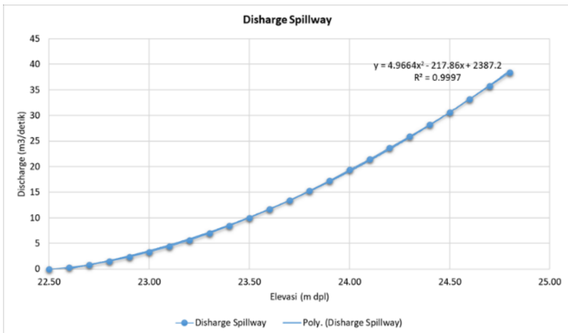

Figure 9. Spillway Capacity Rating Curve for Dam 1.

The inflow-outflow hydrograph shows a reduction in discharge to 6.0 m^3/second. For details, refer to Figure 10.

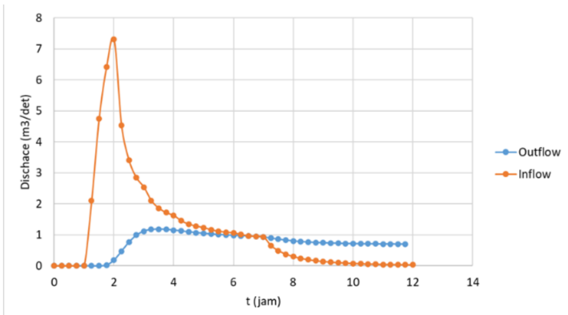

Figure 10. Flood routing (I-O) Hydrograph for Dam 1.

The area of watershed Dam 2 reaches 68.16 hectares (including watershed dam 1 which covers 22.95 hectares), while the area of watershed dam 2 alone is only 45.18 hectares. The average land slope is 11%, and the perimeter of the water body holding runoff is 1592 meters (contour perimeter +16 meters above sea level). The impervious area percentage is 95% (during land processing), and the land roughness value is 0.4 (grassland). The Rainfall Return Period used is 100 years and simulated in a short-duration rain, which is 6 hours. The simulation shows that the maximum runoff discharge that occurs is 14.13 m³/second with the peak time in the second hour of the simulation. The inflow discharge entering watershed dam 2 also comes from the outflow of dam 1. The simulation duration is conducted every 15 minutes to examine the detailed simulation results. The simulation results are presented in the runoff hydrograph as shown in Figure 11.

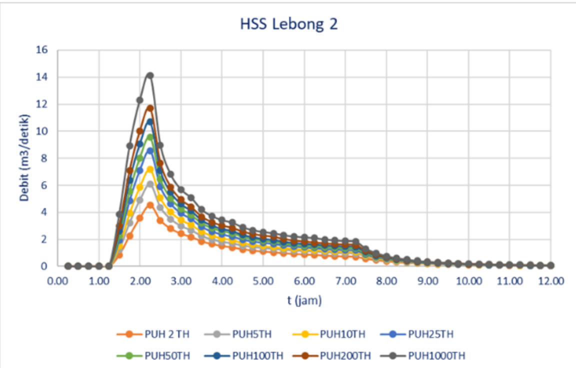

Figure 11. Runoff Hydrograph for Dam 2.

The same method used in dam 1watershed is also applied to dam 2 watershed. The effective height of watershed 2 is 16 meters above sea level, with a total storage volume reaching 77023 m³, and the inundation area is 22000 m². The storage capacity curve and the inundation area of dam 2 can be seen in Figure 12.

The spillway for Dam 2 is designed using an ogee-shaped weir with a square-section control with an effective width of 4.5 meters. The spillway capacity curve can be seen in Figure 13.

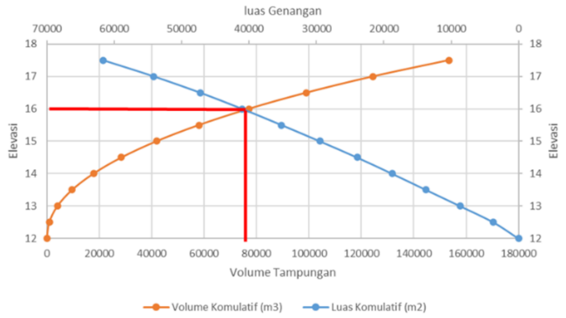

Figure 12. Volume – Area Curve for Dam 2

The maximum discharge at dam 2 is 14.13 m³/second, and the water level at the upstream crest reaches 1.1 meters or at an elevation of 16.10 meters. This condition will be considered to determine the elevation of the dam crest. If the dam crest elevation is at +17.5 meters above sea level, then there is still a 1.5 meters freeboard of the dam crest against the maximum flood discharge.

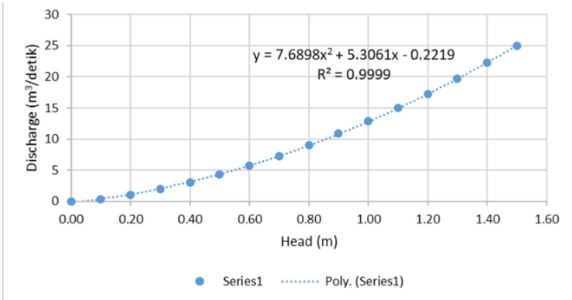

Figure 13. Spillway Capacity Rating Curve for Dam 2.

Dam 2 can reduce flood discharge by 22% from the maximum flood of a 100-year return period. The maximum inflow is 14.18 m³/second, while the outflow through the spillway is 10.99 m³/second. The inflow-outflow hydrograph shows a reduction in discharge to 4.0 m³/second. This condition is due to the low elevation of the spillway and sufficiently wide effective width, but it is safe enough against dam 1 failure.

Referring to the calculations above, the spillway is constructed using a box culvert type with a capacity according to the above results, and the bottom elevation of the box culvert for Dam 1 is at +23.00 m. Meanwhile, at dam 2, it is at +14.30 m.

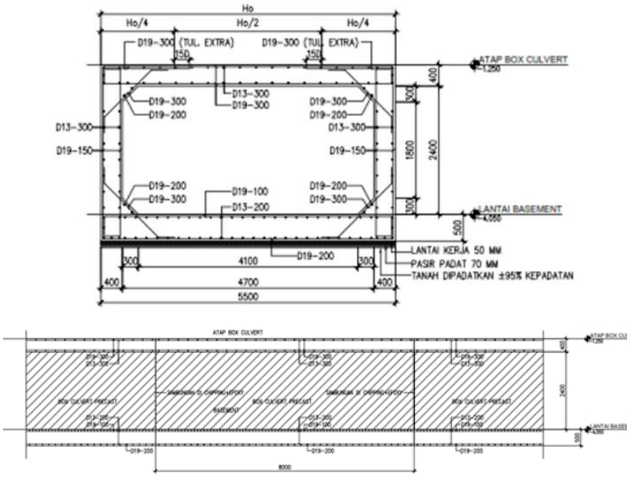

Figure 14. Box Culvert Section Design for Controlling Section of The Spillway.

Based on the calculations above, the flood water elevation is +24.00 m, while Dam 1 Crest is +26.50 m.

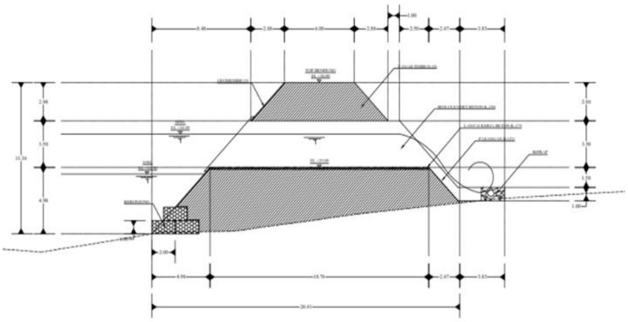

Figure 15. Dam 1 Cross Section.

The flood water elevation is +15.50 m, while the top of the dam 2 crest +16.30 m.

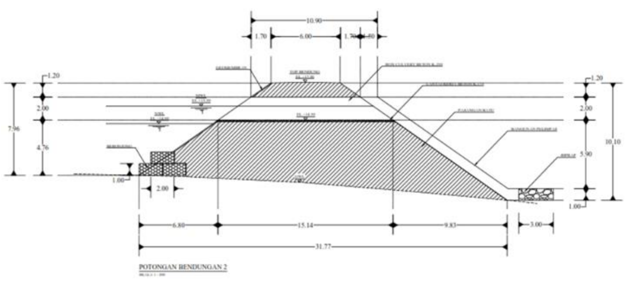

Figure 16. Dam 2 Cross Section.

5. CONCLUSION

The design of small-scale earthfill dams in cascade to meet the irrigation water needs for dryland paddy plantations in West Tulang Bawang, Lampung, consists of 2 dams (Dam 1: upstream; Dam 2: downstream). The catchment area for Dam 1 reaches 22.95 hectares. The effective reservoir storage volume is at elevation 22.5 meters above sea level with a total storage volume of 74039 m^3, and the inundation area reaches 10846 m2. The inflow discharge is 7.3 m^3/second. The area of the watershed for Dam 2 reaches 68.16 hectares (including the watershed of Dam 1 which covers 22.95 hectares), while the area of the watershed of Dam 2 alone is only 45.18 hectares. The effective height of watershed 2 is 16 meters above sea level, with a total storage volume reaching 77023 m^3, and the inundation area is 22000 m^2. To ensure dam safety, a spillway is designed with an ogee crest using a square-section control with effective widths of 3.0 m for Dam 1 and 4.5 m for Dam 2. Flood reduction in the downstream part of Dam 2 reaches 22% and is estimated to be safe to prevent failure due to overtopping hazards. Further research is needed for extreme emergency action plans with simultaneous dam failure scenarios.

REFERENCES

[1] Lewis, B. (2014). Small Dams. CRC Press, London.

[2] PT. Huma Indah Mekar. (2021). Perencanaan Plot Uji Padi Gogo Tahap -1 dan Tahap -2. Kaliandra Lestari. Jakarta.

[3] Asthana, BN, and Khare . D. (2022). Recent Advances in Dam Engineering. Springer. Switzerland

[4] Campos, RGD. and Saliba, APM. (2023). "Methodology to Evaluate Cascade Dam Breaks for Analysis and Safety Design ". Brazilian Journal of Water Resources, Vol. 28, e.16.

[5] Riha, J. Kotaska, S and Petrula, L. (2020). "Dam Break Modelling in Cascade Small Earthen Dams : Case

Study of The Cizinariver in Chech Republic, Water. 12. 2309.

[6] Badan Standardisasi Nasional. (2016). SNI 2415:2016 - Tata Cara Perhitungan Debit Banjir Rencana. BSN.

[7] Badan Klimatologi Meteorologi dan Geofisika. (2021). Data Hujan Harian Maksimum Sta. Radin Inten II, Sta. Lampung Utara, Sta. Pesawaran.