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The Performance of Diversion Channels and Cofferdams of Bener Dam

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Keywords:
cofferdam,
diversion tunnel,
HEC-RAS

ABSTRACT

Bener Dam is one of the new dams built in Bogowonto River, in Guntur Village, Bener District, Purworejo Regency. Bener Dam was constructed to fulfill the irrigation and raw water demand, and also as a flood control, and a micro-hydro power plant, conservation, and tourism that can improve the economy. The diversion works of the Dam consist of the construction of a cofferdam and a diversion tunnel. The cofferdam and diversion tunnel need to be planned well to prevent the river from overflowing through the main dam and causing material losses and casualties. Therefore, it is necessary to study the performance of cofferdam and the diversion tunnel of Bener Dam against the flood discharge. In this study, the diversion tunnel flood routing was carried out by HEC-RAS software version 4.1.0. The design flood uses return periods of 25 and 50 years. The flood routing simulation is carried out by two scenarios: the flow simulation on the existing conditions and the flow simulation on the diversion tunnel. The research results show that the Bogowonto River still can accommodate 25-year, and 50-year floods along the river channel. The cofferdam with a peak elevation of +235 m which is designed with a discharge of 410 m^3/s is also capable of diverting the flood discharge with a return period of 25 years and 50 years. The diversion tunnel of Bener dam is planned by a horseshoe shape F, with a 25-year flood design with 7m tunnel diameter Based on the flood routing analysis, it was found that the maximum water elevation in the diversion tunnel was +221 m, and with outflow of 332 m^3/s. The 50-year flood routing in the diversion tunnel results maximum water elevation of +222 m with an outflow of 396 m^3/s. The flood simulation shows the flow characteristics in the diversion tunnel in the form of open channel flow because the tunnel is not filled by water. Then, the maximum flow velocity on the diversion tunnel is ±14.3 m/s which exceeds the permissible velocity so it can cause damage due to erosion and affect the amount of sediment transport.

1. Introduction

The construction of the Bener Dam in Bogowonto River, Purworejo is one of the government's strategies in resolving the conflict over limited water due to the increase in population and a strategy to fulfill the water needs and agricultural. The cofferdam and diversion channels need to be designed well to prevent the overflow of the river that caused material losses and casualties in the main dam. Therefore, it is necessary to study the performance of cofferdams and diversion tunnels so that they can accommodate flood discharges that may occur during the construction period of main dam. The Bogowonto River flood simulation carried out by HEC-RAS program with the concept of unsteady flow. The flood simulation will show the water surface profile in the existing conditions and in conditions after diversion work using cofferdams and diversion tunnels.

Bendungan Bener, located on the Sungai Bogowonto in Guntur Village, Bener District, Purworejo Regency is a multipurpose dam that utilizes water in the Bogowonto watershed including serving irrigation water needs, and serving water needs, micro-hydropower plants (PLTMH), water conservation, flood control and tourism [1]. The construction site of the Bendungan Bener can be seen in Figure 1 and Figure 2.

2. Method

Two stages of analysis were carried out, namely the hydrology and the hydraulic analysis. Flood routing analysis was carried out using the HEC-RAS program[2], [3]. The results of hydrological analysis will become a benchmark in determining the location, shape and dimensions of flood control buildings [4].

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The data used in hydrological analysis are the annual daily rainfall data and design rainfall to determine the amount of discharge at certain return periods. The flood discharge design calculation carried out by frequency analysis method with several types of probability distributions, namely Normal Distribution, Normal Log Distribution, Normal III Log Distribution, and Gumbel Distribution [5]. The goodness of fit test) carried out by two methods, namely the Smirnov-Kolmogorov Test and the Chi-Squared Test, to determine the suitable probability distribution. The determination of the suitable type of distribution corresponding to the data carried out by several statistical parameters condition that can be seen in Table 1.

Table 1. Parameter requirement condition

Probability distribution	Parameter requirement
Normal	C_s=0, C_k=3
Log-normal	$C_s > 0$, $C_s \cong 3\ C_v$
Log Pearson III	$C_{s\ >}$ 0. $C_{\ v}$ 1.5 C_s 3 + 3
Gumbel	$C_s \cong 1.39$ and $C_k \cong 5.4$

In this study, due to the absence of AWLR (Automatic Water Level Recorder) or historical river flood data, the flood hydrograph calculation approached by unit hydrograph method to describe the rainfall-runoff characteristics of the Bener watershed. Two synthetic unit hydrograph (SUH) methods will be used, namely Nakayasu SUH and SCS SUH.

The HEC-RAS program is used to analyze hydraulics, and with this program, it can simulate steady and unsteady flow simulations to calculate the profile of water levels along river segments. Data inputs for this program include river cross sections, long river sections, river hydraulic parameters (manning and channel slope), building along the river, flow discharge, and water level. Meanwhile, the output of this program is the river flow schemes, cross sections, water level profiles, rating curves, stage and flow hydrographs [6]. This research study the hydraulic capacity of diversion tunnel. The flow characteristics of the diversion channel is divided into two conditions: the free flow is when the entire length of the tunnel has not been filled by water so that the flow characteristics is an open flow; and the pressured flow when the entire length of the cross-sectional channel of the flow is filled with water.

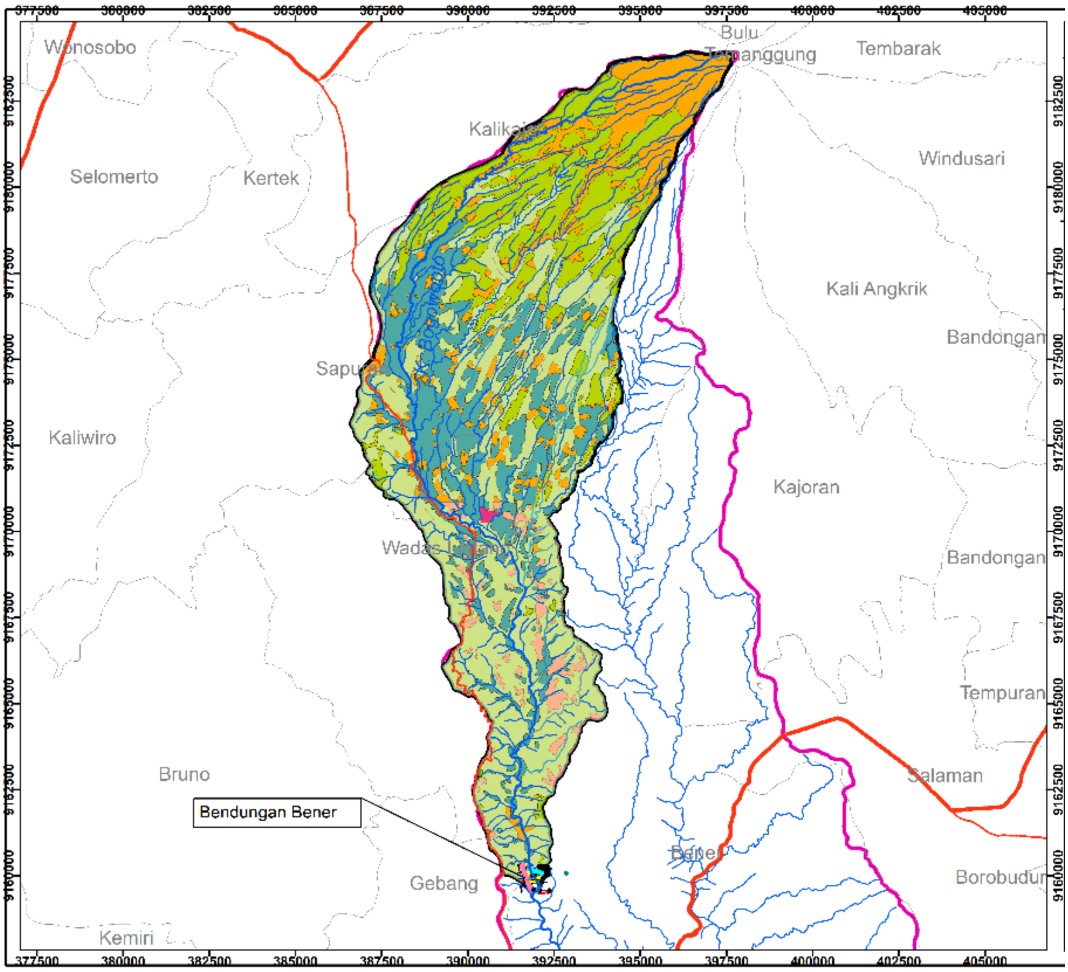

Figure1. Bener Dam project location

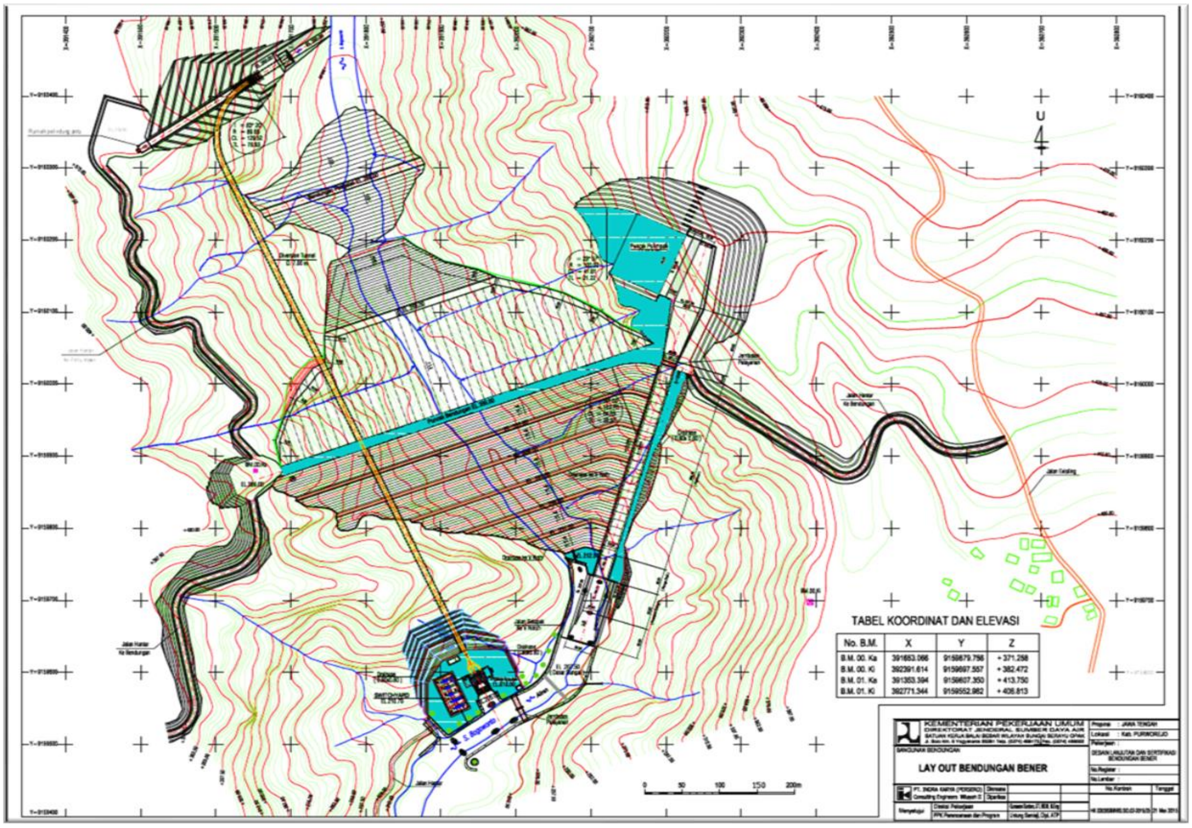

Figure2. Bener Dam layout [1]

3. Results

3.1 Hydrological Analysis

In this study, hydrological analysis aims to determine the characteristics of floods on the Bogowonto River. The design flood is obtained from design rainfall in a watershed system which is transformed using the unit hydrograph method [7]. The design rainfall used is in the form of rain depth in a hyetograph with hourly rainfall distribution as a function of time during heavy rainfall. Three rainfall station data used in this study: Sta. Ngasinan, Sta. Sapuran and Sta. Kepil. The historical rainfall data obtained for 29 years, from 1990 to 2018. The data obtained from BBWS Serayu Opak [1]. The area rainfall was carried out using Thiessen method because it was considered better than other methods. The Thiessen weights obtained are used to find the maximum daily rainfall by summing the multiplication of the Thiessen weights by the daily rainfall depth in each rain sta. The Thiessen weights was adjusted to the availability of rainfall data at each station. Table 2 shows the recapitulation of the annual maximum daily rainfall data.

To calculate the design rainfall, it is necessary to calculate the frequency analysis, which aims to find the relationship between the magnitude of extreme events and the frequency of events using probability distributions using the maximum annual series data such as Table 2. Four probablility distributions observed in this study such as Normal distribution, Log Normal distribution, Gumbel distribution, and Log-Pearson III distribution. The goodness of fit test carried out using Chi-Kudarat and Smirnov-Kolmogorov to obtain the best distribution that fit the rainfall data. Table 3 and Table 4 show the recapitulation results of Chi-Squared and Smirnov-Kolmogorov tests.

Table 2. Maximum daily rainfall in the Bener Watershed (1990-2018)

Year	Maximum rainfall (mm)	Year	Maximum rainfall (mm)
1990	125	2005	110
1991	143	2006	102
1992	238	2007	145
1993	97	2008	110
1994	112	2009	98
1995	131	2010	88
1996	114	2011	157
1997	74	2012	143
1998	105	2013	86
1999	90	2014	111
2000	70	2015	92
2001	110	2016	104
2002	106	2017	112
2003	93	2018	105
2004	87		

Table 3. Chi Squared test results

Probability distribution	Normal	Log Normal	Gumbel	Log Pearson III
$X^{2\ counts}$	11.17	7.38	12.55	1.62
$X^{2\ cr}$	5.99	5.99	5.99	5.99
Information	rejected	rejected	rejected	Accepted

Table 4. Smirnov-Kolmogorov test results

Probability distribution	Normal	Log Normal	Gumbel	Log Pearson III
Δ_{max}	0.21	0.16	0.14	0.10
$\Delta_{critics}$	0.24	0.24	0.24	0.24
Information	accepted	accepted	accepted	accepted

From Chi Square and Smirnov-Kolmogorov test, the best suitable distribution is Log person III. The frequency analysis result rainfall with certain return period. For the diversion works design, the design rainfall uses a 25 and 50 return period. Based on the theory of possibility, which is often referred to as the risk of failure or the possibility of flooding once or more during the lifetime of a water building. The design rainfall based on the Log-Person III distribution can be seen in Table 5.

Rainfall distribution analysis was carried out based on hourly rainfall data for 5 years (2014-2018) obtained from the JAXA satellite [8]with coordinates at Bener Dam. The rainfall data of the TRMM JAXA (GSMap_NRT) is closer to the observation data in three major watersheds in Indonesia: Citarum, Sutami-Brantas, and the Larona watershed than NASA's TRMM (3B42RT) [9]. The rainfall distribution patterns were analyzed using dominant rainfall data with a depth of ≥ 50 mm, which is categorized the heavy rainfall and considered to represent the region studied. The results of rainfall distribution analysis based on satellite data are presented in Table 6 and illustrated in Figure 3 and Figure 4.

Table 5. Design rainfall with a certain return period on Log Person-III distribution.

Return period	Design rainfall (mm)
2	104
5	131
10	151
25	180
50	204
100	231
1000	342

Table 6. Rainfall distribution patterns in the Bener Watershed

Time (hour)	25-year rainfall distribution (mm)	25-year rainfall distribution (mm)
0	0	0
1	5	6
2	13	15
3	25	28
4	27	30
5	27	31
6	23	26
7	20	22
8	17	19
9	12	13
10	8	9
11	4	4
	180	204

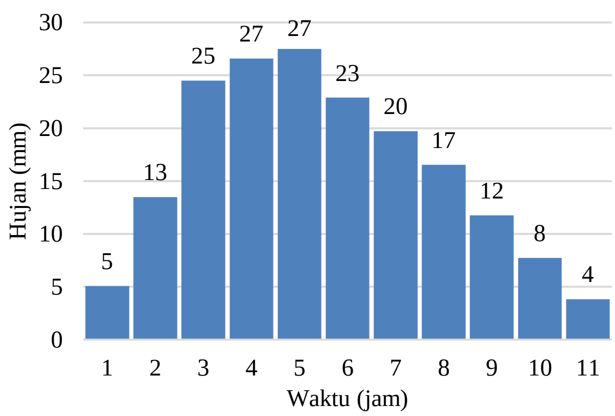

Figure3. The 25-year rainfall distribution patterns of Bener Watershed

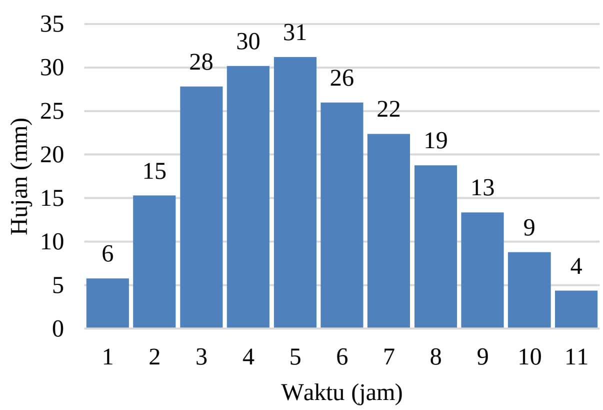

Figure4. The 50-year rainfall distribution patterns of Bener Watershed

The rainfall-runoff transformation method using synthetic unit hydrograph (SUH)[4], [10], [11]. The SUH methods used in this study are Nakayasu and SCS. The parameters used in SUH Nakayasu and SUH SCS are the area of the watershed, the main river length, and the river's slope. The area of the Bener watershed is 113 km^2, the length of the main river is 37 km, and the river slope is 0.08. The analysis results of SUH Nakayasu and SUH SCS can be seen in Table 7 and Table 8. The unit hydrograph result in Figure 5.

According to Harton's theory (Hartonian Overland Flow), surface runoff is rainfall that is not absorbed by the soil by infiltration due to uneven rain and different land cover. In this study, the water loss analysis carried out through the Curve Number (CN) approach with land use data and soil type classification to determine the amount of effective rainfall in the Bener watershed [7]. Based on the hydrological design report of the Bener Dam, the dominant soil type in Bener Watershed is brown Latosol with a percentage value of 46.45% included in the class C soil type with a relatively high runoff potential, the infiltration rate is slow if the soil is saturated. The land use types in the Bener watershed can be seen in Table 9.

From the Bener Watershed land use analysis, a CN value of 69.8, an initial abstraction (*Ia*) value of 23.1, and a retention parameter (*S*) value of 115.4 were obtained. The results of effective rainfall can be seen in Table 10 and Table 11.

Table 7. Nakayasu SUH parameters of Bener Watershed

Parameters		
Watershed Area (A)	113	Km
Main river length (L)	37	km^2
Effective rainfall (Re)	1	Mm
Analysis		
Concentration Time (TG)	2.6	hour
rain unit time (Tr)	1	hour
time from the onset of rain to the peak (T_P)	3	hour
Watershed characteristic coefficient (α)	1.5	
$T_{0.3}$	3.8	hour
Peak flood discharge (Qp)	6.6	m^3/s
$Tp+T_{0.3}$	6.8	hour
Tp + T 0.3 + 1.5T 0.3	12.6	hour

Table 8. SCS SUH paremeters of Bener Watershed

Watershed parameter		
Watershed area (*A*)	112.00	km^2
Main river length (*L*)	37.00	km
Average river slope (*S*)	0.08	
SUH parameter analysis		
Time of concentration (T_c)	2.80	hour
Time Lag (t_l)	1.70	hour
Effective rainfall time (*tr*)	0.40	hour
Time to peak(*Tp*)	1.90	hour
Time base (*Tb*)	4.90	hour
Peak discharge (*Qp*)	12.60	m^3/s

Table 9. Land use in the Bener Watershed

No	Land Use	Broad	CN	CN'
1	Settlements	13	86	1094
2	Plantations/Gardens	70	74	5192
3	Meadow	1	71	49
4	Paddy	0.3	79	25
5	Rainfed Rice Fields	29	83	2448
6	Shrubs	10	79	801
7	River	1	92	94
8	Moor/Field	21	74	1581
	Total	146	146	638

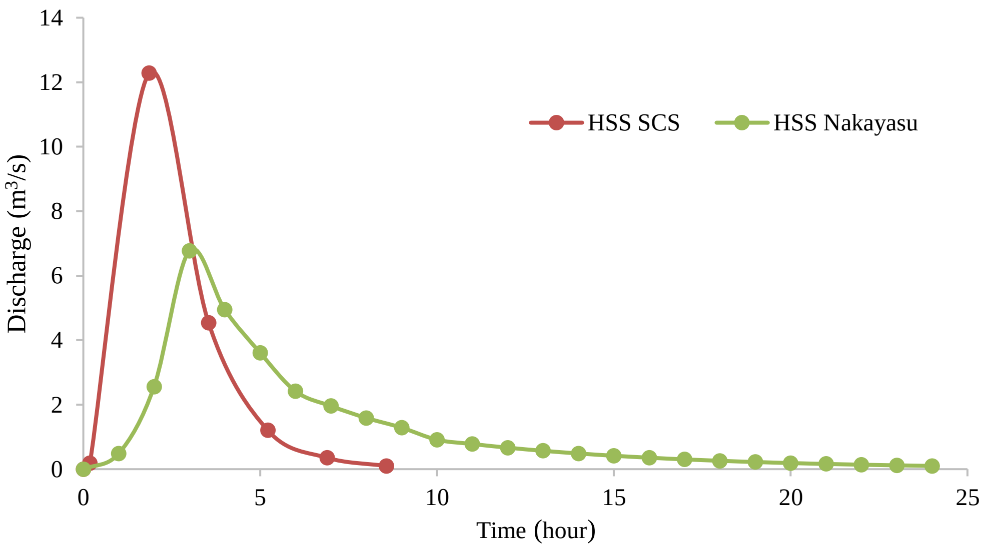

Figure 5. Nakayasu and SCS unit hydrograph

Table 10. 25-years of effective rainfall in the Bener Watershed

Time (hour)	Rainfall (mm)	ΣP	ΣP_{eff}	P_{eff}
1	5.10	5.1	3.3	3.3
2	13.5	18.5	0.2	3.1
3	24.5	43.0	2.9	2.8
4	26.6	69.6	13.4	10.4
5	27.5	97.1	28.9	15.6
6	22.9	120.0	44.2	15.3
7	19.7	139.7	58.6	14.4
8	16.5	156.2	71.3	12.7
9	11.8	168.0	80.7	9.3
10	7.70	175.7	86.9	6.3
11	3.80	179.6	90.1	3.1

Table 11. 50-years of effective rainfall in the Bener Watershed

Time (hour)	Rainfall (mm)	ΣP	ΣP_{eff}	P_{eff}
1	5.80	5.8	3.1	3.1
2	15.3	21.0	0.0	3.0
3	27.8	48.9	4.7	4.7
4	30.2	79.0	18.3	13.6
5	31.2	110.2	37.5	19.2
6	26.0	136.2	56.0	18.5
7	22.4	158.6	73.2	17.2
8	18.8	177.3	88.2	15.1
9	13.4	190.7	99.3	11.0
10	8.80	199.5	106.6	7.4
11	4.40	203.8	110.3	3.7

Flood hydrograph calculations are used to determine the flood design. The calculation is done by multiplying the SUH by the design rainfall. Then, the peak flood discharge will be obtained on a 25-year and 50-year return period, which will be used for hydraulic simulation using HEC-RAS software. The peak discharge recapitulation can be seen in Table 12.

Table 12. Peak discharge of flood hydrograph

Peak Discharge (m^3/s)			
SUH Nakayasu		SUH SCS	
Q_{25}	Q_{50}	Q_{25}	Q_{50}
334	397	302	363

From the two flood hydrographs obtained, SUH Nakayasu was selected and considered to represent the characteristics of the Bener watershed because it has largest peak discharge. In 2016 in the Bogowonto watershed, SUH Nakayasu was the closest hydrograph/similar to a observed hydrograph where hydrological calibration was carried out using HEC-HMS software using 1 data on non-flood events obtained from boro weir data, namely February 25, 2012, and hourly rainfall data from Kradenan station on February 25th, 2012 [12].

3.2. Hydraulics Analysis

The flood routing in this study was carried out hydraulically using HEC-RAS software version 4.1.0. This program aims to determine the river's capacity at the point of review on the Bener Dam diversion channel design with the flood inflow given in the simulation. Furthermore, a simulation of flow routing will be carried out before and after the diversion tunnel with limited geometry data and tunnel dimensions that have been determined in the design of the Bendungan Bener.

In the hydraulic flow simulation, the diversion tunnel design was used from the calculations of the Bener Dam planning consultant by PT. Indra Karya. The dimension of diversion works building as follow:

Diversion tunnel
Tunnel diameter : 7.00 m
Tunnel length : 935.80 m (1 piece)
Form : Horseshoe
Material : Reinforced concrete
Inlet elevation : +225.00 m
Outlet elevation : +207.50 m
Capacity(Q25th) : 410.18 m3/s

Cofferdam
Type : Random fill
Cofferdam peak elevation : +235.00 m
Cofferdam length : 111.83 m
Cofferdam peak width : 10 m
Cofferdam height : 13.80 m

The flood routing in existing conditions aims to determine the capacity of the Bogowonto River in the Bener Dam area in order to identify problems that will occur, so that the dimensions of the diversion tunnel and the height of the cofferdam can be designed to prevent river overflows during main dam construction.

The first step in flow simulation with HEC-RAS is input geometry of the data. The geometry data inputted consist of cross section and long-section of the channel from the field measurement results according to Figure 6 and Figure 7. While manning roughness are adjusted to the field conditions by estimating flow resistance in the channel. This study assumed that the Bogowonto River is a natural channel with plants, so the manning value is around 0.05 – 0.08. The flow simulation on the existing condition (before diversion works) results a water level profile as Figure 8, while the cross-section simulation results presented in Figure 9, Figure 10, and Figure 11.

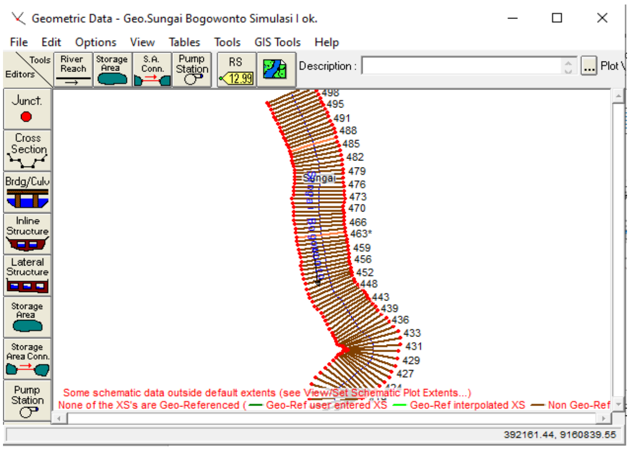

Figure 6. Geometry scheme of the Bogowonto River

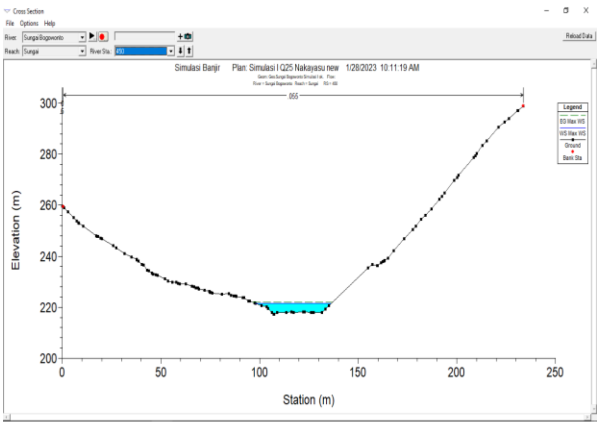

Figure6. Maximum capacity of the inlet of diversion tunnel

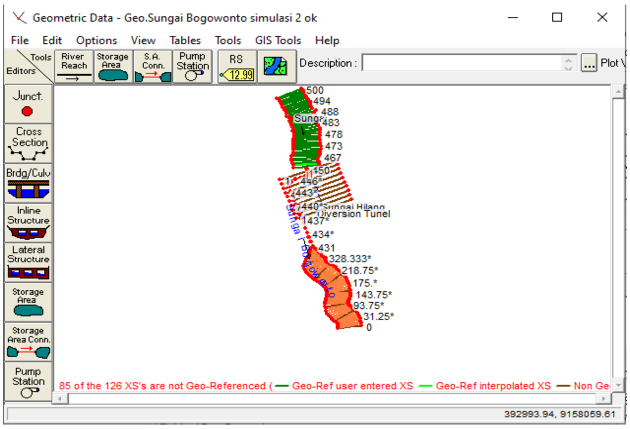

Figure 7. River geometry scheme with diversion tunnel

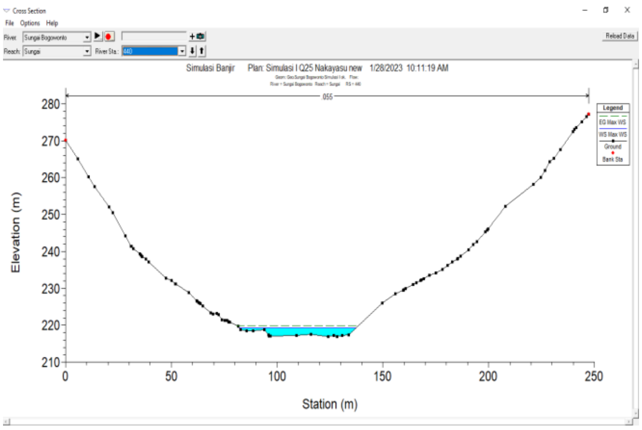

Figure7. Maximum capacity of the cofferdam

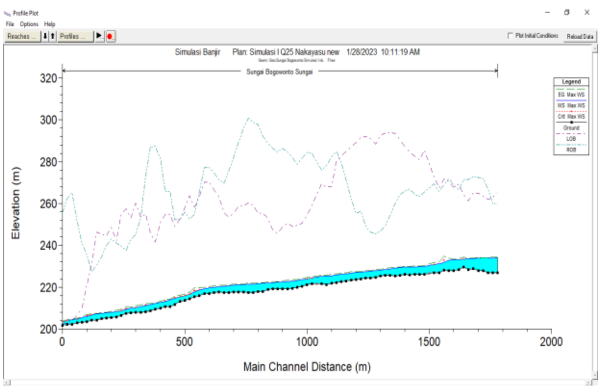

Figure5. Water profile results of the Bogowonto River flood simulation before diversion works

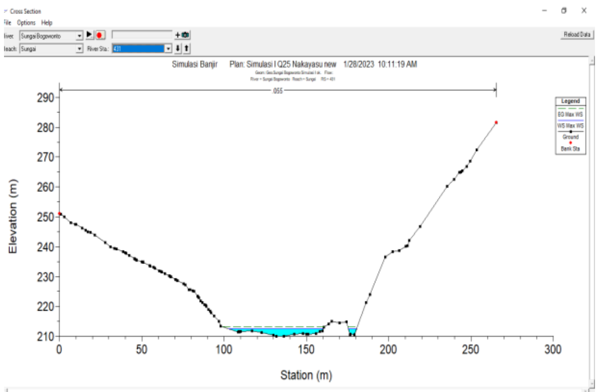

Figure8. Maximum capacity of the outlet of diversion tunnel

The second flow simulation was carried out by adding the diversion tunnel to the geometry data. The Manning's roughness coefficient of the diversion tunnel is adjusted to the of concrete lining in the range of 0.010 – 0.013. The water profile results of the diversion tunnel with inflow of 25-year and 50-year flood can be seen in Figure 12, while the cross-section simulation results presented in Figure 13 and Figure 14.

River capacity analysis aims to determine the maximum flood discharge that the river can accommodate at the review point. In this study, the Bogowonto River capacity is simulated using the measured river geometry around Bener Dam, with reviewing points RS 450, RS 431, and RS 10. The flow simulation type is unsteady flow, with the inflow of Q_{25} (334 m^3/s) and Q_{50} (Q_{50} 397 m^3/s) obtained from hydrological analysis using the HSS Nakayasu method. The river flow simulation shows that at the 25-year return period, RS 450 or in the diversion tunnel inlet has a capacity of 3,714 m^3/s at water elevation of 221 m, RS 431 or in the outlet diversion tunnel has a capacity of 2,277 m^3/s at water elevation of 213 m, RS 10 or in the cofferdam site has a capacity of 2,232 m^3/s at water elevation of 219 m.

Table 13 presents a recapitulation of channel cross sectional capacity in 25-year and 50-year flood simulations in Simulation I (existing condition) and simulation II (after diversion works) while Table 14 present the peak discharge results in each review point.

Table 13. The river cross section capacity at each review point

RS	Simu-lation	Storage capacity			
		Q_{25} (m^3/s)	Elevation (m)	Q_{50} (m^3/s)	Elevation (m)
450	I	3,714	221	4,259	222
	II	3,026	228	3,611	229
431	I	2,277	213	2,717	213
	II	3,521	217	3,918	218
10	I	2,232	219	2,723	219
	II	18,997	228	21,931	229

Table14. The peak discharge at each review point

RS	Simu-lation	Peak discharge			
		Q_{25} (m^3/s)	Elevation (m)	Q_{50} (m^3/s)	Elevation (m)
450	I	332	221	396	222
	II	333	228	396	229
431	I	333	213	396	213
	II	332	217	396	218
10	I	333	219	396	219
	II	0	228	0	229

From the simulation results, The Bogowonto River can accommodate 25-year and 50-year flood up to the maximum capacity as long as there is no overflow along the river channel. The cofferdam design with a peak elevation of +235 m with a flood discharge design of 410 m^3/s can also divert the 25-year and 50-year flood. The perspective plots in simulations I and II can be seen in Figure 15 to Figure 18.

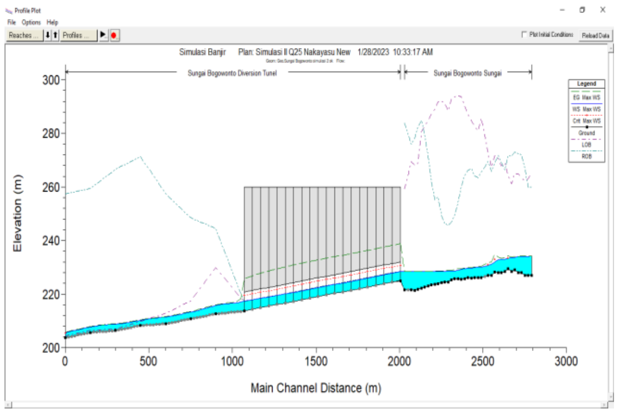

Figure 12. Water profile results of the Bogowonto River flood simulation after diversion works

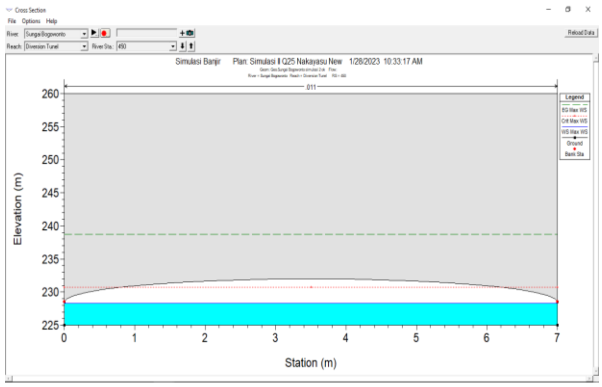

Figure93. Simulation results on the maximum capacity of the inlet of diversion tunnel

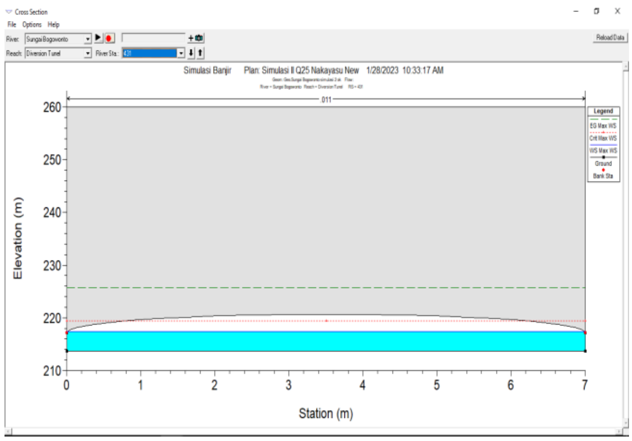

Figure104. Simulation results on the maximum capacity of the outlet of diversion tunnel

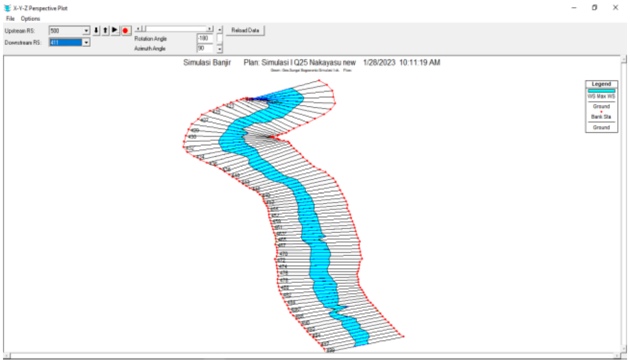

Figure 115. Perspective plot on simulation I Q_{25}.

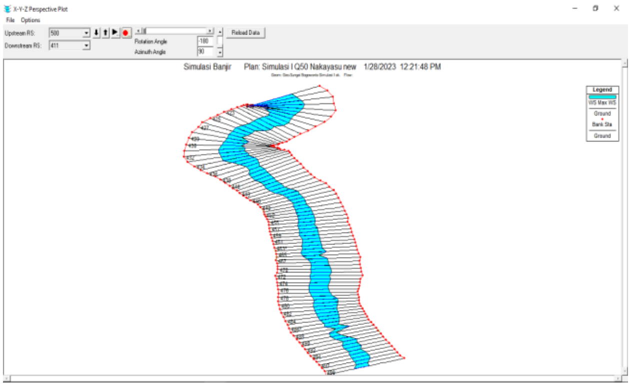

Figure 16. Perspective plot on simulation I Q_{50}.

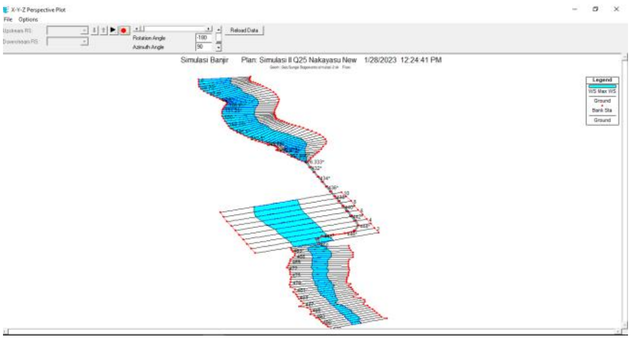

Figure 17. Perspective plot in simulation II Q_{25}.

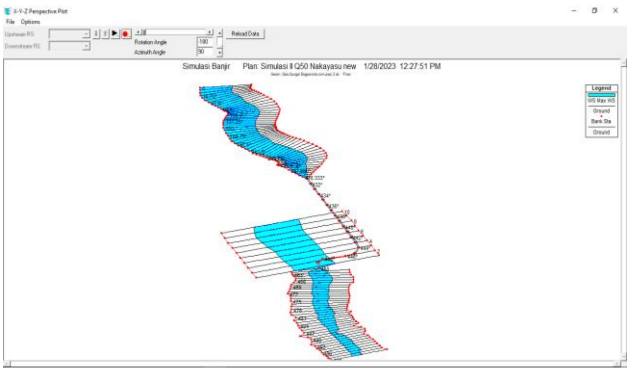

Figure 18. Perspective plot in simulation II Q_{50}.

The Bendungan Bener diversion tunnel is planned to be in the shape of a horseshoe shape F with a 25-year design discharge of 410 m^3/s by the construction consultant. The diameter diversion tunnel is 7 m and from the flood routing analysis, it is found that the maximum water level in the diversion tunnel is +221 m, the outflow discharge is 332 m^3/s, and 50 years return period obtained from the maximum water level in the diversion tunnel is +222 m, and the outflow discharge is 396 m^3/s. The second simulation shows the flow capacity in the diversion channel in the form of open channel flow because the length of the tunnel is not fully fill with water.

In this study, it can be concluded that there is a change in flow velocity between existing conditions and after diversion works that can affect flow characteristics. Flow characteristics must be appropriately reviewed because velocity that exceed their maximum velocity can cause erosion. That it affects the amount of sediment transport so that it can determine the point of the river that needs protection. In the upstream of the diversion tunnel, the froude number 0.6, which means subcritical flow (F<1). In the diversion tunnel, the froude number is 2.4, which means supercritical flow (F>1), and in the downstream of diversion tunnel, the froude number is F 0.94, which means subcritical flow (F<1). The transformation Froude number in the upstream of the tunnel, in the tunnel, and in the downstream of tunnel is due to the difference in channel roughness/manning value. The recapitulation of flow velocities in Simulation I and Simulation II can be seen in Table 15 and Table 16.

Table 15. The flow rate of each review point in Q_{25} simulation

RS	Simulation	Elevation (m)	Flow velocity (m/s)
450	I	221	3.1
	II	228	14.3
431	I	213	3.4
	II	217	12.7
10	I	219	3.7
	II	228	0.0

Table 16. The flow rate of each review point in Q_{50} simulation

RS	Simulation	Elevation (m)	Flow velocity (m/s)
450	I	222	3.4
	II	229	14.9
431	I	213	3.6
	II	218	14.0
10	I	219	3.9
	II	229	0.0

From Table 15 and Table 16, it can be concluded that the Q_{25} and Q_{50} flood simulation with a diversion tunnel results flow velocity 14.3 m/s exceeding the permissible velocity of 10 m/s

4. Conclusion

From the simulation results, The Bogowonto River can accommodate 25-year and 50-year flood up to the maximum capacity as long as there is no overflow along the river channel. The cofferdam design with a peak elevation of +235 m with a flood discharge design of 410 m^3/s can also divert the 25-year and 50-year flood.

The diversion tunnel of Bener dam is planned by a horseshoe shape F, with a 25-year flood design with 7m tunnel diameter Based on the flood routing analysis, it was found that the maximum water elevation in the diversion tunnel was +221 m, and with outflow of 332 m3/s. The 50-year flood routing in the diversion tunnel results maximum water elevation of +222 m with an outflow of 396 m^3/s.

The simulation with diversion tunnels on Q_{25} and Q_{50} passing through the diversion tunnels with a flow velocity of ±14.3 m/s exceeding the permissible speed of 10 m/s so that it can cause damage due to erosion and affect the amount of sediment transport.

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