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Effectiveness Analysis of Meninting Dam's Diversion Tunnel Using HEC-RAS

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Abstract: River diversion is a procedure carried out prior to constructing a dam. It is conducted by diverting water from the main river so that the main dam construction work can be executed at a specifically dry area. In Meninting Dam, the diversion system consists of two main structures, namely cofferdam and diversion tunnel that is equipped with a navigation structure at the upstream part of the tunnel. During the construction, cofferdam experienced overtopping on June 17, 2022. The overtopping most likely occurred because of the diversion tunnel's inability to divert the actual flood effectively during the construction. Therefore, this research aimed to analyse the effectiveness of Meninting Dam's proposed diversion tunnel against design flood discharge for a return period of 25 years. The data used in this research were the updated version of the ones used to design the whole construction of Meninting Dam's diversion system, while the flow conditions along the diversion tunnel were analysed using HEC-RAS. At the same time, the analysis was also carried out using the Level Pool Routing Method as a comparison. The analysis results show that the design flood discharge for a return period of 25 years in Meninting Dam Watershed is 265,62 m^3/s. This causes the water level along the diversion tunnel reach el. +165,95 m above sea level. Taking into account that the cofferdam crest elevation is at +170,00 m above sea level, it could be concluded that Meninting Dam's proposed diversion tunnel, which is 4 m wide and 4 m tall is able to divert the design flood discharge for a return period of 25 years effectively. The investigation results in Meninting Dam Watershed show that the main cause of the overtopping was heavy precipitation. This caused the increasing water level at the upstream part of the cofferdam that resulted to its inability to function properly, taking into account that it was still under construction when it occurred.

Keywords: Dam; Diversion Tunnel; HEC-RAS

Introduction

Dam is a hydraulic structure built across a river channel to control the river flow (Milleanisa et al., 2021; Fakhrulloh et al., 2023; Bharath et al., 2021). It is mandatory to do river diversion before the construction of a dam's main structures begins because the foundation work of the dam and the associated structures must be executed at a dry area (Nurlailin et al., 2021; Hong et al., 2023; Hager et al., 2020). River diversion is carried out by directing streamflow from upstream to downstream using a temporary structure (DengSong et al., 2022; Gayar, 2020). In Meninting Dam, the diversion system consists of 2 main structures, which are cofferdam and diversion tunnel. At the upstream, there is also an open channel installed right before the diversion tunnel. This channel is used as a navigation structure that is supposed to direct the flow into the diversion tunnel.

Design flood discharge with a certain return period used to design the dam must be re-evaluated prior to constructing a dam if there are significant changes applied in the construction schedules (Pusat Pendidikan dan Pelatihan, 2017). The data used to design Meninting Dam were available only up to 2013, while its construction was expected to be finalized in 2022. Taking

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into account that the construction of Meninting Dam was started in 2019 and still under construction until the present time, it is obvious that several adjustments are required in the construction schedules. Therefore, it was necessary to take the major hydrological changes that might have occurred in Meninting Dam Watershed into consideration by re-estimating the design flood discharge in Meninting Dam Watershed using the updated data.

Recent researches (Simatupang et al., 2020; Anga et al., 2022) showed that hydrological characteristics of a watershed tend to change from time to time. Re-evaluation of the hydrological data used to design diversion structures lead to a different design flood discharge, even if the return period did not vary. This also resulted in a different dimension of diversion structures, compared to their first design.

The overtopping of Meninting Dam's Cofferdam that was still under construction on 17th June 2022 most likely occurred because the actual flood exceeded the design flood discharge used to design the diversion tunnel, causing the diversion tunnel's inability to divert the flood discharge effectively. Therefore, this research was intended to analyse the effectiveness of Meninting Dam's proposed diversion tunnel against design flood discharge for a return period of 25 years.

The effectiveness of Meninting Dams's proposed diversion tunnel would be analysed by observing the maximum water level caused by design flood discharge for a return period of 25 years along the diversion tunnel. The effectiveness analysis would be carried out using Hydrologic Engineering Centre-River Analysis System (HEC-RAS), a flood forecasting program. This program is chosen because of its high accuracy and widespread use in river analysis systems (Sami et al., 2016; Albu et al., 2020).

Methods

Research Area

Meninting Dam is located across Meninting River, Meninting Watershed, West Lombok. Geographically, it is located at 80 38' 6.22" S and 1160 21' 37.7" E as shown in Figure 1.

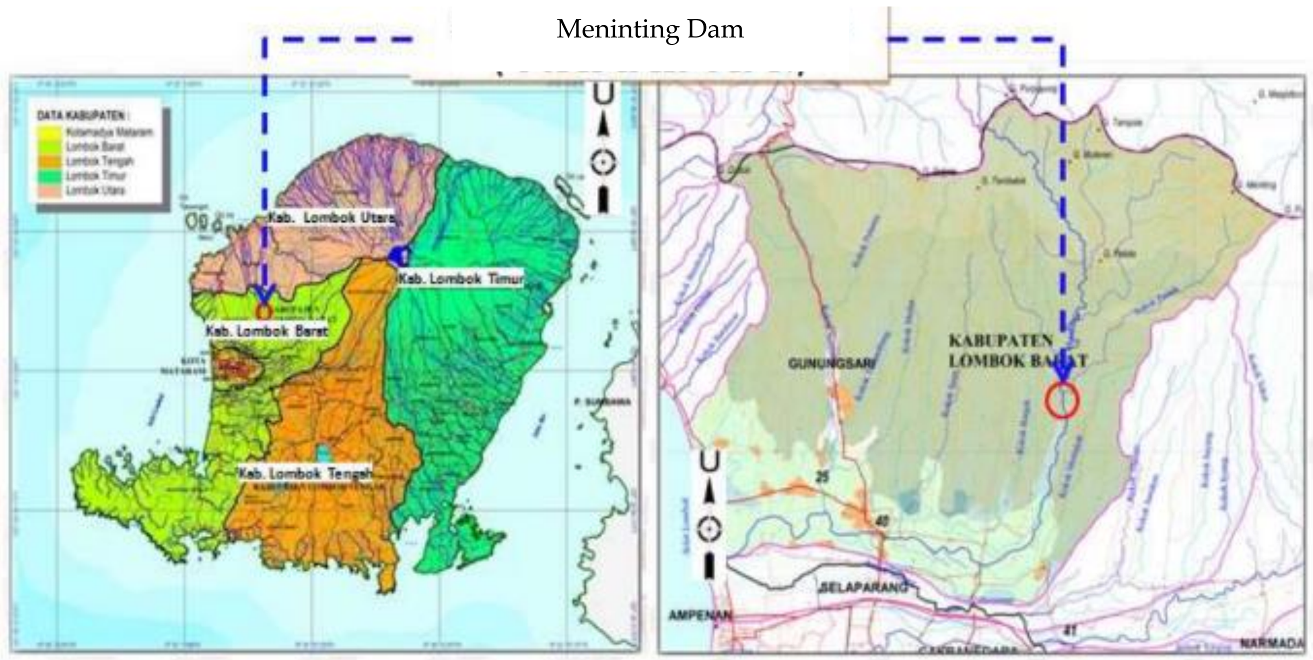

Figure 1. Research Area (PT. Indra Karya (Persero), 2017)

Research Method

This research was carried out using quantitative analysis method, where the analytical framework is shown in Figure 2 and Figure 3 respectively.

Figure 2. Analytical Framework

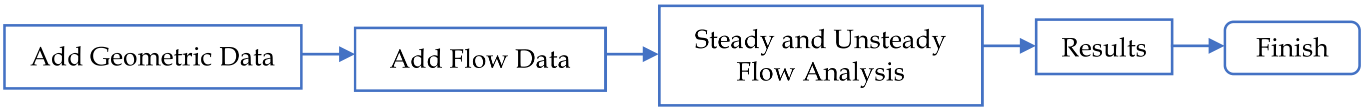

Figure 3. HEC-RAS Modelling Steps

Figure 2 shows the analytical framework of this research, while Figure 3 explains how to create and simulate a model in HEC-RAS. The data used in this research were secondary data obtained from several institutions, such as BWS NT 1 and PT. Indra Karya (Persero). The data included rainfall data from Gunung Sari and Sesaot Rainfall Station from 1993 to 2021, land use patterns in Meninting Dam Watershed, Meninting Dam's reservoir storage capacity curve, topographic maps around Meninting Dam, and technical data of Meninting dam's diversion tunnel.

It was necessary to test the consistency of rainfall data prior to starting the analysis. The purpose was to make sure that the data had no errors and presented the real condition around the research area. In this research, consistency data was tested using Rescaled Adjusted Partial Sums (RAPS) method.

It was also necessary to estimate mean annual precipitation in the watershed, taking into account that the rainfall data used in this research were from more than one rain station. There were several methods that could be used to calculate mean annual precipitation in a watershed. The method used in this research was Thiessen polygon method.

Mean annual precipitation was used to estimate design rainfall in Meninting Dam Watershed, which would eventually be the basis for estimating design flood discharge. In this research, the design rainfall used was the highest value obtained from several distribution functions, including Normal, Log Normal, Gumbel, and Log Pearson Type III.

The design flood discharge for a return period of 25 years was estimated using several synthetic unit hydrograph (SUH) models such as Nakayasu, Gama 1, and SCS. The highest value obtained from those methods was selected as the design flood discharge that must be diverted by the diversion tunnel. The flow conditions along the diversion tunnel caused by the design flood discharge were analysed using HEC-RAS.

The first step that should be executed in HEC-RAS modeling is adding geometric data. The geometric data was supposed to represent the entire situation in the research area. The data used in this step include layout of Meninting Dam's diversion tunnel, manning coefficient along the tunnel, and the tunnel's slope.

Flow data that should be added into the program was the design flood discharge for a return period of 25 years in Meninting Dam Watershed. The unsteady flow analysis could be executed after the geometric data as well as the flow data had been added.

Consistency Data Test

Data consistency must be tested prior to the analysis to ensure that the whole data collection did not contain any errors (Zainal & Zufrimar, 2021; Wahyuni et al., 2021). One of the methods generally used in some previous research (Đurin et al., 2023; Suhartanto et al., 2021) was Rescaled Adjusted Partial Sums (RAPS).

Mean Annual Precipitation

Mean annual precipitation is examined if there are more than one rainfall stations spread around the research area (Triatmodjo, 2008; Bertan et al., 2021). There are a lot of methods that can be used to calculate mean annual precipitation, but a method that is usually used is Thiessen polygon (Bertan et al., 2021; Pala & Yüce, 2023; Chowdhury et al., 2016). The equation used in this method is shown in Formula 1.

$$P = \frac{A_1P_1+\cdots+A_nP_n}{A_2+\cdots+A_n} \quad (1)$$

where:
P = Mean annual precipitation (mm)
$P_1, P_2, \ldots, P_n$ = Precipitation in station 1,…,n (mm)
n = Number of data

Frequency Analysis and Design Rainfall

Table 1: Statistical Characteristics of Distribution Functions

Distribution Function	Requirement
Normal	Skewness (Cs) ≈ 0 Kurtosis (Ck) ≈ 3
Log Normal	Skewness (Cs) ≈ 3 Skewness (Cs) ≈ 3 × Coefficients of variation (Cv)
Gumbel	Skewness (Cs) ≈ 1,1396 Kurtosis (Ck) ≈ 5,4002
Log Pearson Type III	There are no special characteristics for this function.

Frequency analysis is a method used to predict design rainfall for a certain return period (Aurdin, 2019; Ginting & Putuhena, 2017). There are several distribution functions that are widely used to estimate design rainfall in a certain area. Those are normal, log normal, Gumbel, and log Pearson type III. Each distribution function is used under different conditions. Statistical characteristics of the functions are ones of the things that should be considered. Statistical characteristics of each distribution function are shown in Table 1 (Badan Standardisasi Nasional, 2016).

Design Flood Discharge

A synthetic unit hydrograph (SUH) can be used to estimate design flood discharge for a certain return period in a watershed if the watershed does not have any water level recorder or hydrological data (Gayar, 2020). Some SUH models that are commonly used in Indonesia are Nakayasu, Gama I, SCS, and ITB. Nakayasu's model was invented in Japan, while Gama I's model was invented in Java Island (Harto, 1993). On the other hand, SCS' model is usually used to estimate design flood discharge in a relatively large watershed (Gupta, 2017).

Flood Routing

Flow conditions along the diversion tunnel have to be identified prior to flood routing analysis. In a diversion tunnel, there are 2 flow conditions that have to be identified, namely free flow and pressurized flow. Free flow occurred when the tunnel has not been completely filled with water. Otherwise, pressurized flow occurred when the tunnel is already filled with water completely.

The principle applied in flood routing through diversion tunnel is that flood discharge that flows into cofferdam is partially stored in cofferdam reservoir, while the rest of the flood is flowing through the diversion tunnel (Pusat Pembinaan Kompetensi dan Pelatihan Konstruksi, 2005). In other words, flood routing actually represents an equilibrium condition as shown in Equation (**2**).

$$\text{inflow} = \text{storage} + \text{outflow} \quad (2)$$

One of the most applicable methods that can be used in flood routing is level pool routing method.

Flow Conditions along the Diversion Tunnel

Flow conditions along the diversion tunnel can be identified using mathematical equations. One of the equations that is widely used is the Saint Venant equation. There are computer programs that support the mentioned equation. Some computer programs that are commonly used in previous studies are ISIS Flow (Saadi, 2008) and HEC-RAS (Prastica, 2020; Wen et al., 2024).

HEC-RAS

HEC-RAS is a computer program used to visualize hydraulic components of a river (US Army Corps of Engineers, 2016; Daoed et al., 2023; Pratiwi et al., 2023). The analysis of flow conditions along a diversion tunnel using this program requires some data, namely long and cross section data of the tunnel, manning coefficient along the tunnel, and flow discharge diverted into the tunnel. This program is renowned and widely used because of its high accuracy, as well as the fact that it is available for free (Sami et al., 2016; Albu et al., 2020). Previous studies (Mihu-Pintilie et al., 2019; Patel et al., 2017; Dasallas, et al., 2019) stated that flow conditions along a channel could be accurately modeled using HEC-RAS 1D. Compared to the other flood forecasting programs such as MIKE 21, HEC-RAS is more favorable because it provides a visualization that can give the users better understandings regarding the hydraulic conditions (Shrestha et al., 2020).

Results and Discussion

Effectiveness analysis of Meninting Dam's diversion tunnel was carried out through several steps. The first step was consistency data test, whose result is shown in Table 2.

Table 2: Results of Consistency Data Test for Each Rainfall Station

Value of	Rainfall Station	
	Gunung Sari	Sesaot
$\frac{\mathbf{Q}}{\sqrt{\mathbf{n}}}$	0.68	1.30
$\frac{\mathbf{Q}}{\sqrt{\mathbf{n}}}$ table	1.46	1.46
$\frac{\mathbf{R}}{\sqrt{\mathbf{n}}}$	1.22	1.62
$\frac{\mathbf{R}}{\sqrt{\mathbf{n}}}$ table	1.69	1.69

Table 2 shows that the rainfall data from Gunung Sari and Sesaot Rainfall Station are consistent, thus they could be used for the basis of further analysis.

The consistent rainfall data from Gunung Sari and Sesaot Rainfall Station were then used to estimate mean annual precipitation in Meninting Dam Watershed. The method used to estimate mean annual precipitation was Thiessen polygon. This method was chosen by taking into account that rain stations in this watershed were not spread evenly. Figure 4 shows Thiessen polygon that had been drawn using QGIS, a program supporting geographic information system (GIS).

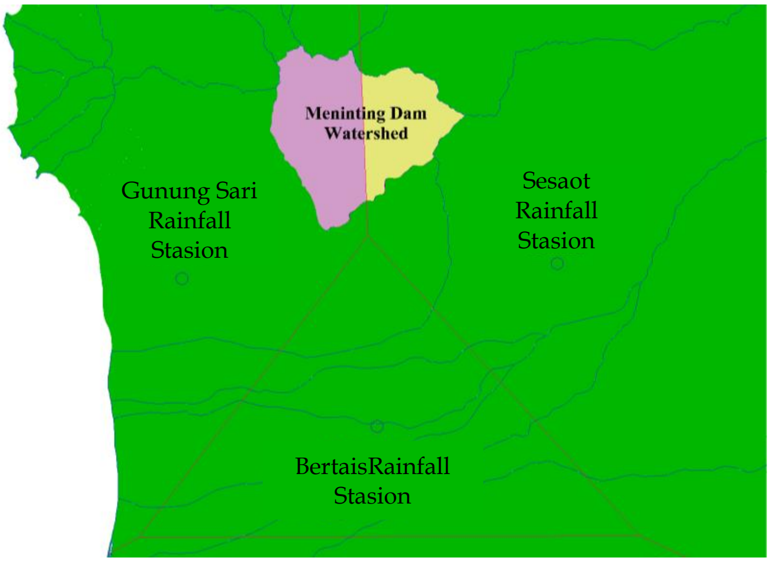

Figure 4. Thiessen Polygon Drawn Using QGIS

From Figure 4, the total area affected by each rain station could be obtained. Based on the affected area, the mean annual precipitation was then able to be calculated using (1), with the result shown in Figure 5.

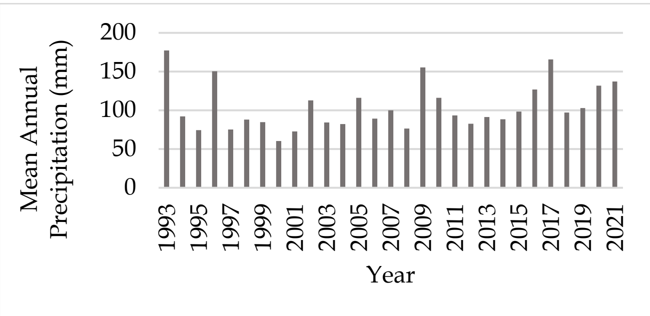

Figure 5. Mean Annual Precipitation in Meninting Dam Watershed

Based on Figure 5, the maximum mean annual precipitation occurred in 1993, while the minimum mean annual precipitation occurred in 2000. In 2021, which was the closest year to 2022 (the time when Meninting Dam's Cofferdam experienced overtopping), the mean annual precipitation in Meninting Dam Watershed is 137 mm. The various mean annual precipitation in Meninting Dam Watershed from time to time was one of the reasons why it was necessary to re-estimate the design flood discharge in Meninting Dam Watershed.

Design rainfall has to be estimated prior to estimation of design flood discharge. In this research, design rainfall was estimated through frequency analysis, which was carried out with several probability distribution functions. From the analysis, the characteristics of each distribution function showed that the distribution functions that fit the criteria stated in Table 1 were normal and Gumbel distribution. However, those characteristics alone were not sufficient to represent the hydrological characteristics in Meninting Dam Watershed. Therefore, it was necessary to do a goodness of fit test for each distribution function. The methods were chi-square and Smirnov-Kolmogorov. The result of goodness fit test is shown in Table 3.

Table 3: Design Rainfall for a Return Period of 25 Years in Meninting Dam Watershed

Distribution Function	Design Rainfall (mm)	Goodness of Fit Test: Chi-Square Method	Goodness of Fit Test: Smirnov-Kolmogorov Method
Normal	155.311	x^2 = 0.14 (Acceptable)	Δ_p max = 0.16 (Acceptable)
Log Normal	159.256	x^2 = 0.14 (Acceptable)	Δ_p max = 0.270 (Not Acceptable)
Gumbel	176.039	x^2 = 0.14 (Acceptable)	Δ_p max = 0.095 (Acceptable)
Log Pearson Type III	168.057	x^2 = 0.14 (Acceptable)	Δ_p max = 0.222 (Not Acceptable)

Table 3 shows that Normal and Gumbel distribution functions pass all the qualifications required in Chi-Square and Smirnov-Kolmogorov method. This indicates that those distribution functions are deemed usable in estimating design rainfall in Meninting Dam Watershed. Between these two methods, Gumbel's method delivers a higher value of design rainfall in the watershed. In order to anticipate its occurrence, the design rainfall for a return period of 25 years in Meninting Dam Watershed was selected from Gumbel's method, whose value is 176,039 mm. On the other hand, Log Normal and Log Pearson Type III distribution functions did not meet the qualifications required in Chi-

Square and Smirnov-Kolmogorov method. Hence, these methods could not be used.

The design rainfall was used to estimate design flood discharge for a return period of 25 years in Meninting Dam Watershed. Several synthetic unit hydrograph (SUH) models, including Nakayasu, Gama 1, and SCS were employed in the analysis. The result of design flood discharge from each model is shown in Figure 6.

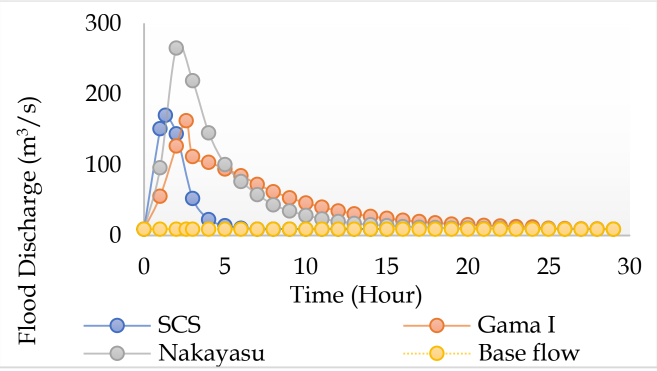

Figure 6. Design Flood Discharge for a Return Period of 25 Years in Meninting dam Watershed

Figure 6 shows that the highest value of design flood discharge for a return period of 25 years in Meninting Dam Watershed is produced by Nakayasu's model. Therefore, the flood discharge in Meninting Dam Watershed was set to be 265,62 m^3/s. This value was adopted in the analysis of flow conditions along the diversion tunnel. Design flood discharge for a return period of 25 years represents the inflow that flows through Meninting Dam's diversion tunnel.

In this research, the flow conditions were analysed twice. The first analysis was flood routing through Meninting Dam's diversion tunnel using level pool routing method. The purpose of this analysis was to analyse the flow conditions at the inlet of the tunnel. The second analysis was carried out using HEC-RAS to analyse the flow conditions along the entire section of the diversion tunnel, including its navigation structure in the upstream part of the tunnel.

Flood routing through Meninting dam's diversion Tunnel was conducted at the inlet of the tunnel, which is horseshoe shaped. The method used in this analysis was level pool routing, with the data used to support the analysis are listed below (PT. Indra Karya (Persero), 2017):

- Diameter of diversion tunnel	:	4 m
- Manning coefficient	:	0.014
- Length of the tunnel	:	382,5 m
- Slope	:	0.01
- Invert elevation of the tunnel	:	+147.80 m
- Cofferdam crest elevation	:	+170.00 m

There are 2 types of flow conditions that have to be considered in Meninting Dam's diversion tunnel. Those are free flow and pressurized flow. Free flow occurred when the water level in the tunnel is 0 to 4 m. When the water level in tunnel reaches more than 4 m, pressurized flow starts to form.

Flood routing through Meninting Dam's diversion tunnel was carried out using level pool routing by considering the 2 conditions mentioned earlier. The result of the analysis is shown in Figure 7.

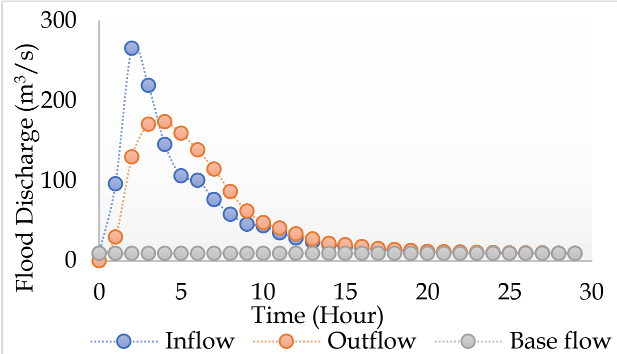

Figure 7. Flood Routing through Meninting Dam's Diversion Tunnel

Figure 7 shows that the inflow entering the diversion tunnel is directly proportional with the outflow released from the tunnel. The rising inflow will result in the rising outflow and vice versa, until they eventually almost reach the base flow. Design flood discharge for a return period of 25 years in Meninting Dam watershed which is 265,62 m^3/s will make the maximum outflow reach 174,04 m^3/s. This shows that the diversion tunnel is able to reduce 34,45% of the flood discharge in Meninting Dam Watershed.

Water level in the diversion tunnel when the outflow is maximum could be obtained from the rating curve shown in Figure 8.

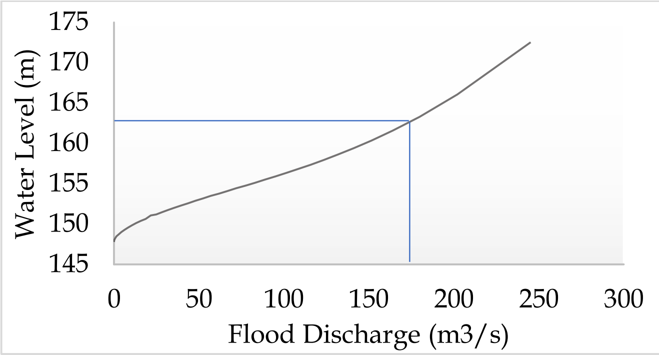

Figure 8. Rating Curve in Meninting Dam's Diversion Tunnel

Based on Figure 8, it can be seen that the outflow released from the tunnel which is 174,04 m^3/s will cause the maximum water level in the tunnel reach el. +162,66

m. The result obtained in this research and the one shown in the previous design given by the consultant slightly varied. The variation is shown in Table 4.

Table 4: Result of this Research Compared to the Original Design

	Inflow (m^3/s)	Max Water Level (m)	Maximum Outflow (m^3/s)
Result from this Research	265.62	162.66	174.04
The Original Design	274.14	166.25	178.95

Table 4 shows that the result of the analysis is not very different from the original design given by PT. Indra Karya (Persero). The re-estimation of design flood discharge for a return period of 25 years in Meninting Dam Watershed resulted in a slightly smaller value, compared to the design flood discharge with the same return period estimated by the consultant. Therefore, it is still necessary to do a recalculation of design flood discharge in the watershed if the construction schedules changed significantly, taking into account that hydrological characteristics tend to change from time to time.

For the second analysis, the modeling of flow conditions along the diversion tunnel was carried out using HEC-RAS as both steady and unsteady flow. In order to represent the real situation at the dam site, the geometric data added into HEC-RAS have to resemble the layout of the diversion tunnel. This layout is shown in Figure 9.

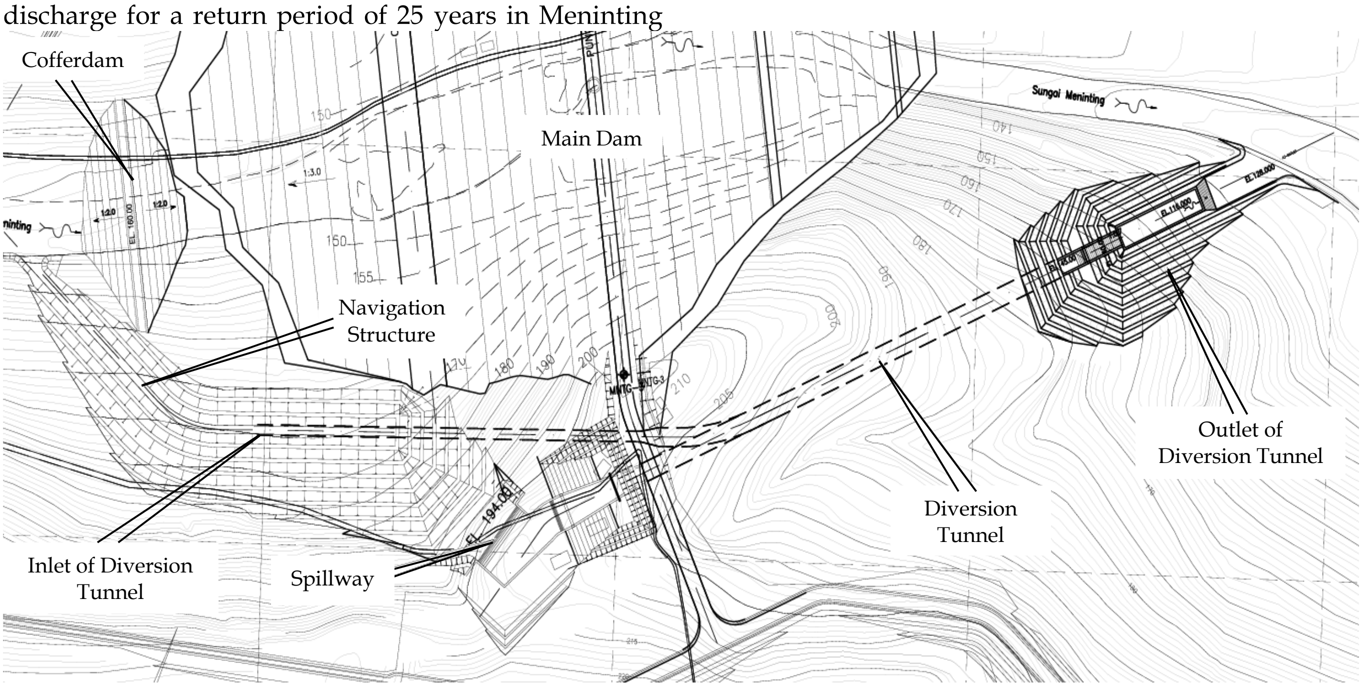

Figure 9. Layout of Meninting Dam's Diversion Tunnel (PT. Indra Karya (Persero), 2017)

The representation of the layout in Figure 9 is illustrated in HEC-RAS as shown in Figure 10.

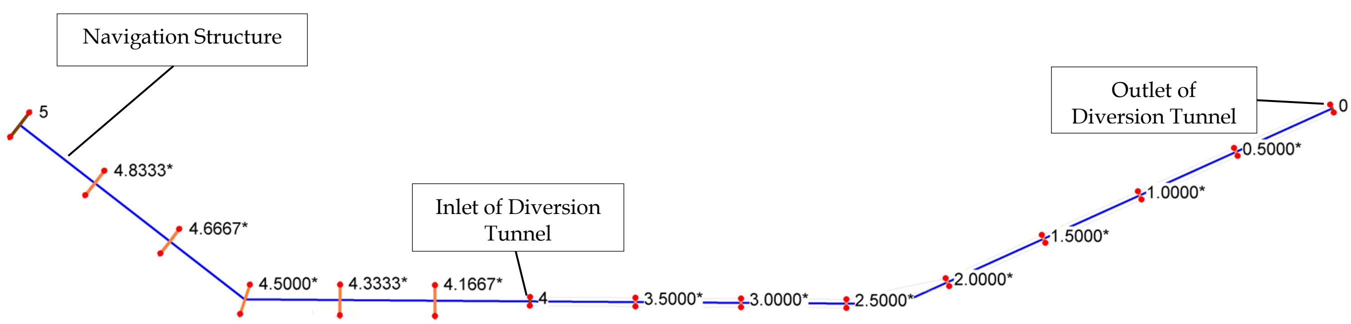

Figure 10. Geometric Data

One of the components of geometric data in HEC-RAS is cross section. In Figure 10, the red lines represent the cross section created in several points along the diversion tunnel. The numbering of these cross sections has to be conducted from downstream to upstream.

The final model shows that unsteady flow is deemed more fit to represent the real condition in the research area, considering that the flow conditions modeled as unsteady flow resulted in a more similar value to the one obtained from flood routing through Meninting Dam's diversion tunnel, compared to the one modeled as steady flow.

Navigation structure at the upstream part of the tunnel was modeled as a trapezoidal open channel whose length is 262,5 m, while the diversion tunnel was modeled as a rectangular open channel with additional circular lid on top, hence rather similar to horseshoe shaped diversion tunnel which is 382,5 m long. The rest of the data used in this model were the same with the data used in flood routing through Meninting Dam's diversion tunnel.

The flow conditions along Meninting Dam's diversion tunnel analysed using HEC-RAS are presented in Figure 11, Figure 12, Figure 13, and Figure 14 respectively.

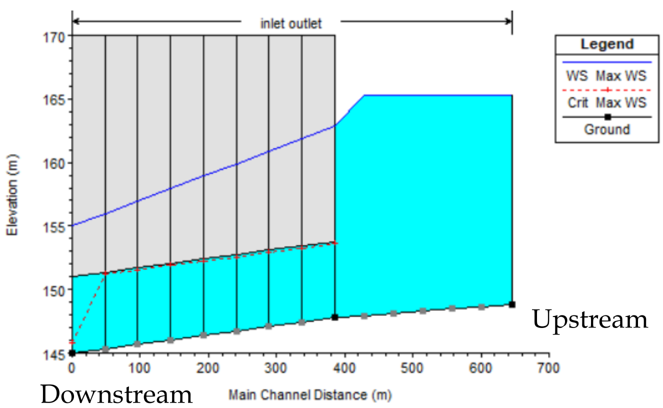

Figure 11. Long Section of Meninting Dam's Diversion Tunnel

In Figure 11, the upstream part of diversion tunnel is located at the right side, while the downstream part is located at the left side. The gray area represents Meninting Dam's Cofferdam, whose crest elevation is at +170,00 m.

The modeling of cross sections in HEC-RAS was conducted from downstream to upstream. It was rather different from the numbering of stations (STA) that was carried out from upstream to downstream.

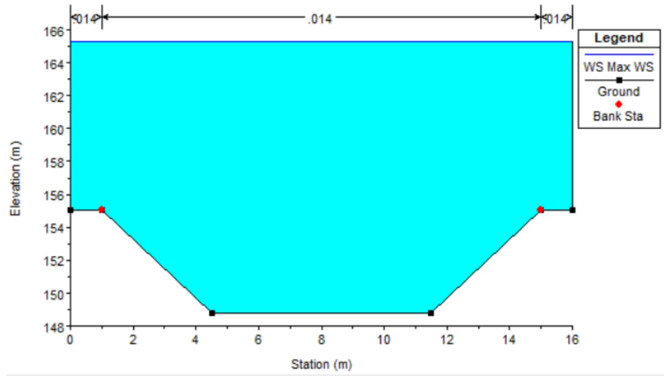

Figure 12. Flow Condition at STA 0+00 m (Navigation Structure)

The navigation structure in the upstream is named as STA 0+00 m. It is shown in Figure 12 that design flood discharge for a return period of 25 years which is 265,62 m^3/s causes the maximum water level in the section reach el. +165,33 m and even exceeds the channel's capacity. This condition is not badly affecting the dam's construction, considering that the cofferdam crest elevation is at el. +170,00 m, which is higher than the maximum water level in the diversion tunnel.

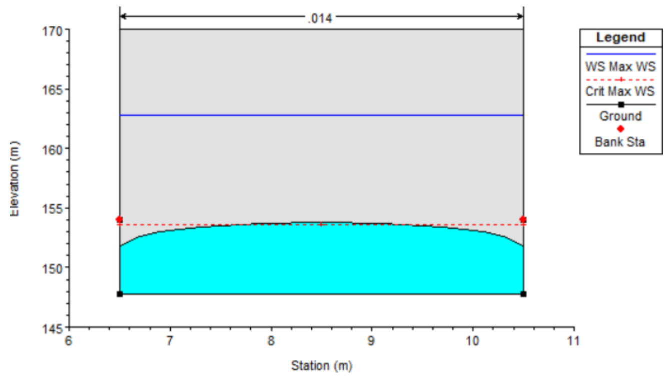

Figure 13. Flow Condition at STA 0+262,5 m (Inlet of Diversion Tunnel)

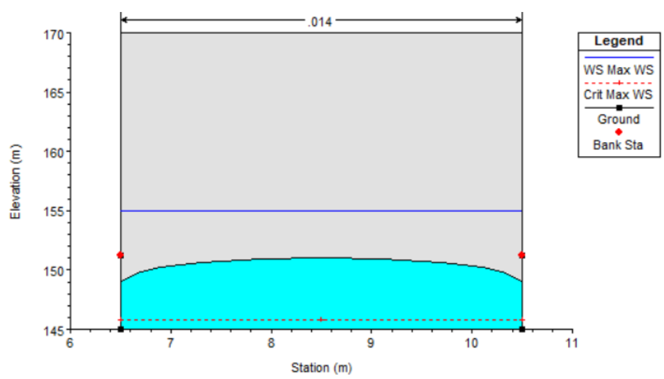

Figure 14. Flow Condition at STA 0+00 m (Outlet of Diversion Tunnel)

When the water started flowing into the tunnel, design flood discharge for a return period of 25 years will fill the tunnel thoroughly, forming pressurized flow along the diversion tunnel. Flow condition in the inlet of the tunnel is shown in Figure 13, while the flow condition in the outlet of the tunnel is shown in Figure 14.

Conclusion

Design flood discharge for a return period of 25 years in Meninting Dam Watershed after the recalculation is slightly different from design flood discharge with the same return period proposed in the original design. This variation is caused by re-evaluation of hydrological data. Design flood discharge for a return period of 25 years in the watershed proposed in the original design is 274,14 m^3/s, while the result of the recalculation is 265,62 m^3/s. The analysis of flow condition along Meninting Dam's diversion tunnel which was proposed to be 4 m long and 4 m tall, whose shape is trapezoidal for navigation structure at the upstream part of the diversion tunnel and horseshoe for the diversion tunnel shows that the maximum water level along the diversion tunnel is +165,95 m above sea level. Taking into account that the cofferdam crest elevation is at el. +170,00 m above sea level, it could be concluded that the proposed diversion tunnel of Meninting Dam is able to divert the design flood discharge for a return period of 25 years in Meninting Dam Watershed effectively during Meninting Dam's construction. It could be confirmed that the overtopping of Meninting Dam's Cofferdam that previously occurred was not caused by the diversion tunnel's inability to divert the flood discharge effectively. The investigation results in Meninting Dam Watershed showed that the main cause of the overtopping was heavy precipitation. This caused the increasing water level at the upstream part of the cofferdam that resulted to its inability to function properly, taking into account that it was still under construction when it occurred.

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Author Contributions

The first author, S.F.G., contributed in designing, executing, and writing the article. Y.S. and E.S., listed as the second and third author, provided guidance throughout the writing process until completion. I.W.Y., S., and A.S., positioned as the fourth, fifth, and sixth author respectively, contributed to validating the article's instruments. All authors have given their approval for the manuscript to be published.

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Conflicts of Interest

The authors confirm that there are no conflicts of interest associated with the publication of this article.

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