U Karst
Volume 08 Number 01 Year 2024

ISSN (*Online*) 2581-2157
ISSN (*Print*) 2502-9304

Available Online at
https://ojs.unik-kediri.ac.id/index.php/ukarst/index

https://dx.doi.org/10.30737/ukarst.v8i2.6192

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Flood Risk Analysis for the Construction of the Patimban Port Access Toll Road

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A R T I C L E I N F O

Article History :

Article entry : 01 – 11 – 2024
Article revised : 11 – 11 – 2024
Article received : 08 – 12 – 2024

Keywords :
Flood Modelling, Flood Risk Analysis, Hydrology Analysis, Soil Conversation Service Method, Surface Water Modelling System (SMS).

IEEE Style in citing this article:

A. A. D. Noviantoro, F. Mulyawati, and R. S. Nurvita, "Flood Risk Analysis for the Construction of the Patimban Post Access Toll Road," U Karst, vol 8, no. 2, pp 134 – 148, 2024, doi: 10.30737/ukarst.v8i2.6192.

A B S T R A C T

In recent decades, the risk of flooding in the Cipunagara River area has increased due to global climate change causing more extreme rainfall patterns. The planned construction of the Patimban Port Access Toll Road has a strategic role in supporting national logistics connectivity. However, the geographical location of the planned toll road in the lowlands near the Cipunagara River poses a significant risk to the sustainability of the infrastructure. This study aims to analyze the risk of flooding in the Cipunagara River and its impact on the design of the toll road. Hydrological analysis was carried out using rainfall data from eight observation stations for the period 2012–2021. Analysis of frequency distribution, rainfall intensity and the Soil Conservation Services (SCS) Unit Hydrograph method was carried out to calculate peak flood discharge. Modeling was carried out using Surface Water Modeling System (SMS) software. The results of the study indicate that the Cipunagara River Basin (DAS) has high rainfall variability with the potential for extreme rainfall in large return periods. The peak discharge of the 100-year return period is 1003.582 m^3/second, indicating the risk of extreme flooding because it exceeds the river capacity of 309.31 m^3/second. The results of flood modeling show that the flood water level in the 100-year return period reaches +8,908 meters, which confirms the need for a minimum toll road infrastructure elevation of +9,908 meters to meet the vertical clearance standard. These findings provide a significant contribution to the planning of toll road infrastructure that is more resilient to flood risks, supports operational sustainability, and reduces potential economic losses.

1. Introduction

Building disaster-resistant infrastructure is an increasingly urgent need, especially when facing climate change and extreme weather events. Toll roads, as the backbone of national connectivity, must be designed to withstand the threat of floods, earthquakes or other natural

ISSN (*Online*) 2581-2157
ISSN (*Print*) 2502-9304

disasters that have the potential to disrupt operations and user safety. Careful planning taking into account risk analysis and mitigation is essential to ensure the long-term sustainability and efficiency of this infrastructure.

The plan to build the Patimban Port Access Toll Road, which connects the industrial area with Patimban Port, will pass through various rice fields, irrigation canals, and small and large rivers [1], [2]. One of the main challenges in constructing this toll road is crossing the Cipunagara River, which is known to experience flooding during high-intensity rain frequently [3]. This happened in February 2021 when heavy rain with high intensity caused the Cipunagara River to overflow and affected 1427 houses [4]. In addition, flooding also occurred in December 2022 which caused the embankment to break and many residents were evacuated [5]. This river is characterized by high peak discharge during the rainy season. This problem poses serious risks to toll road design and operations, such as damage to bridge structures and connectivity disruption due to inundation. Therefore, an in-depth analysis of flood risk and appropriate mitigation measures are needed to minimize the impact of flood disasters.

Disaster-resilient infrastructure design requires a holistic approach integrating data-driven risk analysis and the latest technologies. Hydrological analysis is needed to determine rainfall patterns, peak discharge and frequency of flood events, while hydrodynamic modeling is used to map the spatial and temporal distribution of inundation. Combining these two methods ensures that structural designs such as bridges and toll roads can withstand extreme hydrological loads. This approach increases infrastructure resilience to disasters, supports operational sustainability, and reduces potential economic losses and social impacts due to disaster disruption.

Previous research has discussed the importance of integrating hydrological and hydraulic analysis in infrastructure planning, especially those in flood-prone areas [6]–[8]. These studies show that hydrodynamic modeling based on return period peak discharge data can accurately represent the distribution of inundation and flood risk [9]. Insufficient bridge elevation above the flood water level is often the main cause of infrastructure damage during extreme rainy seasons [10]–[12]. In addition, other research emphasizes the importance of evaluating river capacity in handling return period peak discharge to mitigate flood risk [13]–[16]. In Indonesia, similar research has also been carried out in other areas, such as the Bengawan Solo and Ciliwung watersheds, which identified a relationship between flood discharge and cross-river infrastructure design [17], [18]. However, research that specifically examines the characteristics of the Cipunagara River and its impact on the construction design

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of the Patimban Port Access Toll Road is still limited. This is important so that the toll road that has been built can be protected from flood disasters.

This research aims to analyze the risk of flooding on the Cipunagara River and its impact on toll road design. By utilizing hydrological analysis and hydrodynamic modeling, this research is expected to be able to provide a comprehensive picture of the characteristics of the Cipunagara watershed, flood water level, inundation areas, and mitigation measures needed to support safe and efficient Patimban Port Access Toll Road infrastructure planning. The results of this research can be used in designing toll roads that can face flood risks.

2. Research Method

The research began with collecting rainfall data from eight observation stations in the Cipunagara watershed area for 2012 to 2021, followed by analysis of average rainfall using the Thiessen Polygon method. Next, the rainfall data is analyzed using the frequency distribution method (Gumbel, Log Normal, Log Pearson III, and Normal) to determine the planned rainfall based on a certain return period. Rain intensity is calculated using the Mononobe method, then used as input in calculating flood discharge using the Soil Conservation Services (SCS) Unit Hydrograph method. Peak discharge from various return periods is calculated to model flood water level elevation using Surface Water Modeling System (SMS) software version 11.2.12. This modeling produces visualization of inundation areas and evaluation of flood water level at the planned toll road crossing point with the Cipunagara River. The results of this modeling are then analyzed to provide recommendations for infrastructure design, including minimum bridge heights and flood risk mitigation measures around the area.

2.1 Data Collection

Secondary data is used obtained from related agencies. Rainfall data was taken from eight observation stations spread across the Cipunagara watershed area, namely Kasomalang, Sindanglaya, Bantarhuni, Subang, Pagaden, Tambakdahan, Panamanukan, and Pusakanagara stations for the period 2012 to 2021. This data includes the annual maximum daily rainfall required for average and frequency rainfall analysis. In addition, topographic data for the Cipunagara watershed area was obtained to help model river flow and flood inundation using SMS software. Data on the maximum capacity of the Cipunagara watershed is used to identify potential flooding based on planned flood discharge calculations.

2.2 Hydrological Analysis

The initial step of hydrological analysis is carried out by calculating the average rainfall using the Thiessen Polygon method to determine the contribution of each rain station

https://dx.doi.org/10.30737/ukarst.v8i2.6192

ISSN (*Online*) 2581-2157
ISSN (*Print*) 2502-9304

to regional rainfall. Next, annual maximum rainfall data were analyzed using four frequency distribution methods (Gumbel, Log Normal, Log Pearson III, and Normal) to determine the planned rainfall at various return periods. Next, a method suitability analysis was carried out using the parameters Cs (skewness coefficient, Equation 2) and Ck (kurtosis coefficient, Equation 3) with Sd (standard deviation, Equation 1), $\bar{X}$ (average value of the variate), X_i (value of the i-th variate), and n is the number of data.

$$Sd = \sqrt{\frac{\sum(X_i - \bar{X})^2}{n-1}} \tag{1}$$

$$Cs = \frac{n\sum_{i=1}^{n}\{(X_i) - \bar{X}\}^3}{(n-1)(n-2)Sd^3} \tag{2}$$

$$Ck = \frac{\frac{1}{n}\sum_{i=1}^{n}\{(X_i) - \bar{X}\}^4}{Sd^4} \tag{3}$$

The suitable method will be validated using the Chi-Square and Kolmogorov-Smirnov tests. Rain intensity is calculated using the Mononobe method to describe rainfall distribution within a certain time duration at each return period. The results of this rain intensity are used to calculate flood discharge using the SCS Unit Hydrograph method.

2.3 SCS Unit Hydrograph Analysis

SCS (Soil Conservation Service) Unit Hydrograph Analysis was carried out to calculate the planned flood discharge based on the characteristics of the Cipunagara watershed. This method begins with collecting planned rainfall data. This data is then used to determine effective rainfall patterns. In this analysis, watershed parameters such as area (1,360 km^2), river length, slope, and lag time are calculated to determine the peak time (Tp) and base time of the hydrograph (Tb). The peak time is calculated by considering the hydrological coefficient of the watershed, while the base time is calculated as a function of the peak time. Peak discharge (Qp) is calculated using the maximum discharge formula, which considers effective rainfall, watershed area, and rain duration. This peak discharge can be used as input for flood modeling using SMS software.

2.4 SMS Modelling

Flood modeling using the Surface Water Modeling System (SMS) was carried out to visualize flood inundation areas. Cipunagara watershed topographic data in a Digital Elevation Model (DEM) is used to determine the profile of the river bed and surrounding area. Maximum peak discharge data is included as the main input in the model. Modeling was carried out using a 2D hydrodynamics module, which allows spatial surface flow analysis to describe the distribution of inundation around the river. During the modeling process, boundary conditions

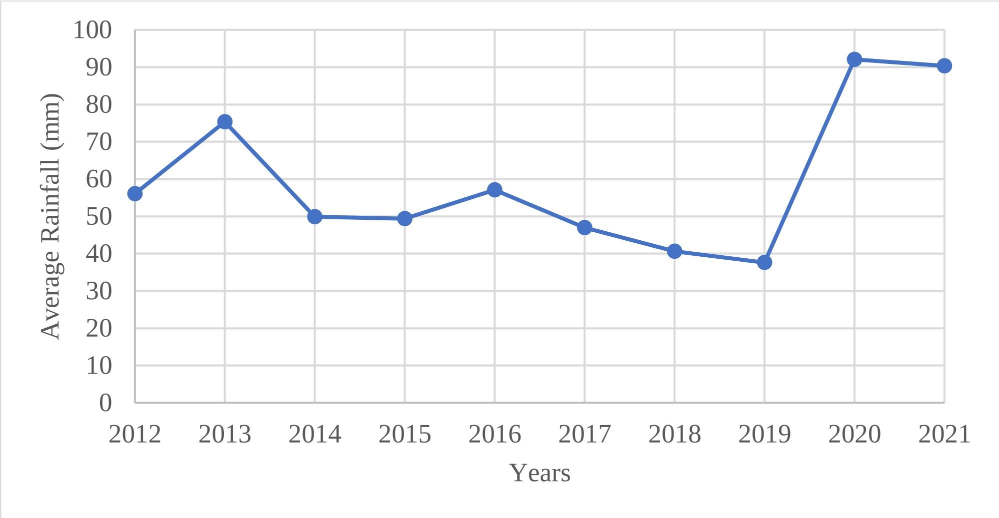
https://dx.doi.org/10.30737/ukarst.v8i2.6192

ISSN (*Online*) 2581-2157
ISSN (*Print*) 2502-9304

and hydraulic parameters, such as the Manning roughness coefficient, are determined based on the river's and watershed's physical characteristics. Simulations are carried out to predict flood water level and inundation distribution

3. Results and Discussions

3.1 Rainfall Analysis



Source: Author's Calculation Results (2024).

Figure 1. Average Rainfall from 2012-2021

Based on **Figure 1**, the results of rainfall analysis using the Thiessen Polygon method, the annual average rainfall for the Cipunagara watershed during the 2012–2021 period was 59.53 mm. This value is calculated by considering each rainfall station's influence area in the region. Annual rainfall fluctuations show patterns that vary every year. In 2012, the average rainfall was recorded at 56.04 mm. 2013 showed a significant increase with average rainfall reaching 75.34 mm. However, in 2014 there was a sharp decline to an average value of 49.89 mm and 49.39 mm in 2015. Furthermore, the average rainfall in 2016 increased to 57.05 mm, indicating a rainy season with higher intensity. In 2017 and 2018, rainfall fell again with values of 46.95 and 40.65 mm. 2019 recorded the lowest average rainfall of 37.59 mm. In the last two years of the analysis period, namely 2020 and 2021, there was a spike in average rainfall of 92.07 mm and 90.38 mm respectively, indicating the potential for extreme rainfall which could impact flood discharge in this region.

These rainfall fluctuations illustrate the climate dynamics and topographic conditions of the Cipunagara watershed. This rainfall fluctuation pattern is strongly influenced by global phenomena [19]. High rainfall, such as that in 2020 and 2021, shows the vulnerability of watersheds to flooding, especially during peak discharge. On the other hand, low rainfall such

https://dx.doi.org/10.30737/ukarst.v8i2.6192

ISSN (*Online*) 2581-2157
ISSN (*Print*) 2502-9304

as in 2019 indicates the possibility of a longer period of drought or dry season. These findings emphasize that rainfall patterns in the Cipunagara watershed require attention in planning and mitigating flood risks, especially regarding the construction of toll road infrastructure across this area. This is because there was a spike in rainfall in 2020 and 2021 which has been proven to cause flooding and this rainfall may increase in the following years.

3.2 Frequency Analysis

Rainfall frequency analysis is used to determine planned rainfall in various periods with the results shown in **Table 1**.

Table 1. Results of Rainfall Frequency Analysis

Period (Year)	Gumbel (mm)	Log Normal (mm)	Log Pearson III (mm)	Normal (mm)
2	57.617	56.877	62.621	59.534
5	81.057	74.006	72.559	76.031
10	96.574	84.949	75.293	84.672
25	116.185	95.096	76.819	91.741
50	130.732	108.135	77.326	99.793
100	145.171	118.054	77.569	105.292

Source: Author's Calculation Results (2024).

For the 2 year period, the Log Pearson III distribution produces the highest rainfall of 62,621 mm, followed by the Normal method of 59,534 mm, while the Gumbel distribution provides a value of 57,617 mm which is lower than the other methods. In the 5 year period, the Gumbel method begins to provide higher rainfall values, namely 81,057 mm, followed by the Normal method at 76,031 mm. The Log Pearson III and Log Normal distributions produce lower values of 72.559 mm and 74.006 mm respectively. From 25 years to 100 years, the Gumbel distribution consistently produces the highest planned rainfall values. For example, in 100 years, the Gumbel method gives rainfall of 145,171 mm, while the Log Normal, Log Pearson III, and Normal methods produce values of 118,054 mm, 77,569 mm, and 105,292 mm, respectively. Based on this data, each method will be validated to determine the most appropriate method. The analysis results are shown in **Table 2**.

https://dx.doi.org/10.30737/ukarst.v8i2.6192

Table 2. Method Suitability Analysis Results

No	Distribution Type	Requirements	Calculation Result	Description
1	Gumbel	$C_s \leq 1.14$	0.851	Meet
		$C_k \leq 5.4$	1.675	Meet
2	Log Normal	$C_s = Cv^3 + 3Cv = 0.23$	0.506	Does not meet
		$C_k = Cv^8 + 6Cv^6 + 15Cv^4 + 16Cv^2 + 3 = 3.1$	2	Does not meet
3	Normal	$C_s \approx 0$	0.851	Does not meet
		$C_k \approx 3$	1.675	Does not meet
4	Log Person III	Apart from the above values and $C \neq 0$	-	-

Source: Author's Calculation Results (2024).

Table 2 shows the results of the method suitability analysis using the parameters Cs (skewness coefficient) and Ck (kurtosis coefficient). The Gumbel distribution meets the criteria with a Cs value of 0.851 (≤ 1.14) and Ck of 1.675 (≤ 5.4), so it is declared suitable. On the other hand, the Log Normal distribution fails to meet the criteria because the Cs (0.506) and Ck (2) values do not meet the requirements. The Normal distribution is also unsuitable because the Cs value (0.851) is not close to 0 and the Ck value (1.675) is not close to 3. For the Log Pearson III distribution, suitability analysis does not need to be carried out because from the three previous methods there are already criteria that meet

The Gumbel distribution which has been declared to meet the requirements of the Cs and Ck parameters is also further validated using a distribution goodness-of-fit test. The two test methods used are the Chi-Square and Kolmogorov-Smirnov tests. The test results show the calculated chi square value is 3.6 and the critical chi square is 5,991. This value shows that the Gumbel method can be used because the calculated chi square value is smaller and the chi square is critical. Apart from that, the Kolmogorov-Smirnov test results showed a Dmax value of 0.338 and Do 0.41. Because the Dmax value is smaller than Do, it can be concluded that the Gumbel distribution statistically meets the data suitability and can be used as a reliable method for analyzing rainfall frequency.

3.3 Rain Intensity

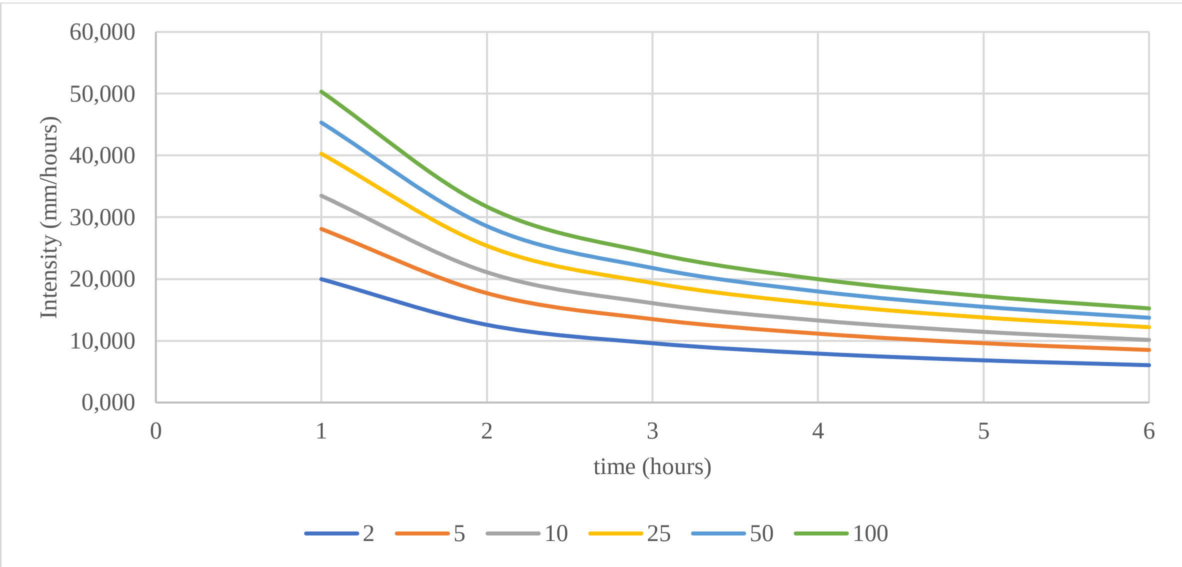
Rain intensity calculations were carried out to describe rainfall in various return periods with the results shown in **Table 3**.

ISSN (*Online*) 2581-2157
ISSN (*Print*) 2502-9304

Table 3. Rainfall Intensity (mm/hour)

Time (hour)	Period					
	2	**5**	**10**	**25**	**50**	**100**
0	0	0	0	0	0	0
1	19.975	28.101	33.480	40.279	45.322	50.328
2	12.583	17.702	21.091	25.374	28.551	31.705
3	9.603	13.510	16.096	19.364	21.789	24.195
4	7.927	11.152	13.287	15.985	17.986	19.973
5	6.831	9.610	11.450	13.775	15.500	17.212
6	6.049	8.510	10.140	12.199	13.726	15.242

Source: Author's Calculation Results (2024).



Source: Author's Calculation Results (2024).

Figure 2. Intensity Duration Frequency

Rain intensity decreases as the duration of each return period increases. For the 2 year return period, the highest rainfall intensity occurred at 1 hour at 19,975 mm/hour and decreased to 6,049 mm/hour at 6 hours. Similar trends were also observed in other return periods, such as in the 100-year period, with the highest intensity being 50,328 mm/hour at 1 hour and decreasing to 15,242 mm/hour at 6 hours.

This decrease in rain intensity shows that rainfall tends to be more distributed as the duration of time increases. This is in accordance with previous research where the longer the duration of the rain, the intensity will decrease [20]. Apart from that, rain intensity tends to

https://dx.doi.org/10.30737/ukarst.v8i2.6192

increase over a longer return period [21]. This was also found in this analysis where higher rainfall intensity over a long return period, such as 50 years or 100 years, indicates the potential for extreme rainfall which could influence peak flood discharge in the river basin. This is important in infrastructure planning and flood risk mitigation, especially for development in vulnerable areas. Rainfall intensity can be used as a basis for determining infrastructure height, and mitigation steps to anticipate the impact of flooding.

3.4 Flood Discharge

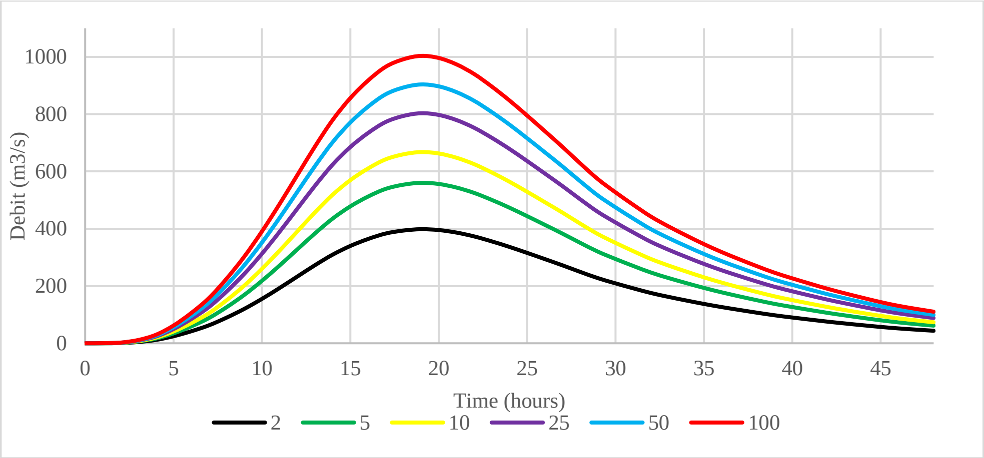
Flood discharge is a key parameter in hydrological analysis that describes the magnitude of the flow. The results of the flood discharge analysis are shown in **Table 4**.

Table 4. Flood Discharge Analysis Results

Parameter	Calculation Results
Qp (Peak Discharge)	17,491 m^3/second
Tp (Maximum Time)	16,75 hours
Tb (Minimum Time)	100,53

Source: Author's Calculation Results (2024).

Based on **Table 4**, the peak discharge (Qp) resulting from the analysis is 17.491 m^3/second. This peak discharge shows the maximum flow during high-intensity rain events in the Cipunagara watershed. Peak time (Tp), namely the time required to reach maximum discharge after the start of the rain event, was recorded at 16.75 hours. This reflects the hydrological response of the watershed to the rainfall that occurs. Meanwhile, the minimum time (Tb), which describes the total duration of flood runoff, was recorded at 100.53 hours. The results of the peak discharge calculation above are used to calculate the design flood discharge with several return periods. The results of the design flood discharge are shown in **Figure 2**.



Source: Author's Calculation Results (2024).

Figure 3. Design Flood Discharge

https://dx.doi.org/10.30737/ukarst.v8i2.6192

ISSN (*Online*) 2581-2157
ISSN (*Print*) 2502-9304

Based on **Figure 3**, the design flood discharge shows a pattern of increasing peak discharge as the return period increases. For the 2 year return period, the maximum discharge was recorded at 398,321 m³/second, which continued to increase until it reached the highest value of 1003,582 m³/second at the 100 year return period. The graph also shows that the maximum discharge occurs around 15-20 hours after the rain starts, before the discharge slowly decreases to initial conditions. This trend of increasing peak discharge at each return period is in line with previous research, which shows that peak discharge tends to increase significantly for longer return periods due to greater frequency of extreme rain and higher rain intensity [22].

Based on these results, it was found that the Cipunagara watershed has a high risk of peak discharge. The peak discharge value in all periods has exceeded the maximum discharge capacity of the river which is only 309.31 m³/s. This shows the great potential for water overflows leading to flooding in the watershed area, especially during extreme rain events. Maximum discharges that exceed river capacity reinforce the need to consider flood risk mitigation, such as creating retention ponds, increasing river capacity, and building flood-resistant infrastructure [23]. In planning the toll road that crosses the Cipunagara watershed, these results are an important basis for ensuring that the design of bridges, culverts and drainage channels can handle this potential flood.

3.5 Flood Modelling

Flood modeling is carried out using software to validate the potential for flooding and identify areas with the potential to be inundated. This modeling uses peak discharge data for a return period of 100 years is 1003.582 m³/s, because this is the highest discharge in all return periods. The modeling results are presented in **Figure 4.**

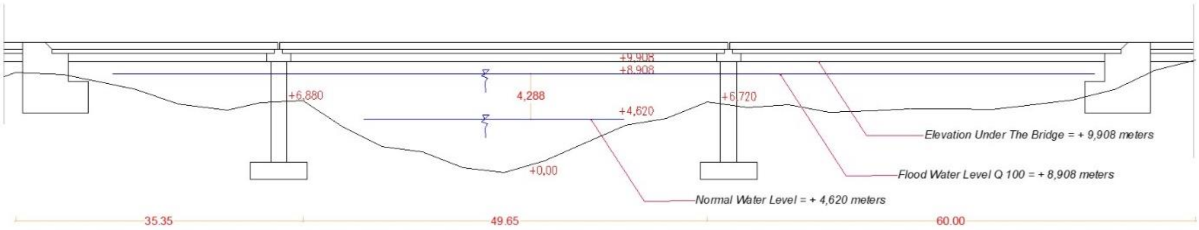
Source: Author's Calculation Results (2024).

Figure 4. Modelling Result

https://dx.doi.org/10.30737/ukarst.v8i2.6192

ISSN (*Online*) 2581-2157
A. A. D Noviantoro/ U Karst Vol 08 No.02 Year 2024
ISSN (*Print*) 2502-9304

Figure 4 above shows the simulation results of flood inundation areas based on peak discharge for a 100 year return period. Areas marked in blue reflect areas that could potentially be flooded during extreme floods with an inundated area of 215,033.96 m^2. This modeling shows that inundation covers a fairly large area around the watershed, including the area around the toll road planned to cross the area. Identified inundations include residential areas, agricultural land and parts of the planned toll road route. This potential for inundation emphasizes the need for in-depth evaluation of infrastructure design to minimize the risk of flood damage. Modeling also indicates that several critical points, such as toll road crossings over rivers, require special attention to ensure sufficient freeboard elevation. This is important to ensure smooth toll road operations during the high-intensity rainy season. The results of the flood water level analysis are shown in **Figure 5**.



Source: Author's Calculation Results (2024).

Figure 5. River Cross Section

The flood water level analysis results show that the flood water level for the 100 year return period discharge reached +8,908 meters, while the normal water level was +4,620 meters from the river bed. Based on these results, the planned bottom elevation of the bridge is at least +9,908 meters from the river bed. This is determined based on the Circular Letter of the Minister of PUPR Number: 07/SE/M/2015, which states that bridge planning must have a vertical clearance of at least 1 meter above the floodwater level. This 1 meter freeboard is very important to ensure the operational safety of toll roads during the flood season, avoiding potential disruption due to standing water approaching the bridge construction elevation [24]. Flood water level elevations at peak discharge periods of large return periods, such as 100 years, will greatly influence infrastructure design in flood-prone areas. Previous research clearly states the importance of considering maximum flow discharge over a long period to obtain a safe design against flooding [25]. Apart from that, it is recommended that land be filled up for the right and left areas of the Cipunagara River that are flooded, especially those that are crossed by the planned toll road construction. This backfill aims to increase the elevation of the area so that it meets the minimum height criteria.

https://dx.doi.org/10.30737/ukarst.v8i2.6192

ISSN (*Online*) 2581-2157
ISSN (*Print*) 2502-9304

This research provides a recommendation for a minimum elevation of +9,908 meters from the river bed to ensure the operational safety of the bridge against flooding. These findings support toll road infrastructure planning across the Cipunagara watershed and contribute to practical understanding of the importance of integrating peak discharge data and flood modeling in mitigating hydrological disaster risks. In addition, implementing these results can increase infrastructure resilience to flooding, reduce potential economic losses, and maintain transportation connectivity.

4. Conclusion

The Cipunagara watershed has high rainfall variability with the potential for extreme rainfall in large return periods, significantly influencing peak discharge and flood risk. The research results show that the peak discharge for the 100-year return period is 1003.582 m^3/second, which indicates the risk of extreme flooding because it exceeds the river capacity of 309.31 m^3/second, with inundation areas including residential areas, agricultural land and planned toll road routes. Flood modeling indicates that the flood water level at the 100-year return period reaches +8,908 meters, confirming the need for toll road infrastructure elevations of at least +9,908 meters to meet vertical clearance standards. These findings emphasize the importance of integrating hydrological analysis and flood modeling in infrastructure planning to minimize the risk of flooding in toll road projects. So it can increase infrastructure resilience and reduce the risk of economic loss in the Cipunagara watershed area.

5. Acknowledgment

The author would like to thank the Departement of Civil Engineering, Faculty of Engineering, Langlangbuana University. Thank you to the lecturers who have provided knowledge, guidance and direction. Thank you also to my parents, wife, family and friends who always pray for and encourage the author.

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