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http://dx.doi.org/10.30737/ukarst

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Flood Modeling of Jatiroto River Using HEC-RAS to Determine Effective Flood Control Alternatives

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ARTICLE INFO

ABSTRACT

Jatiroto River, located on the border of Lumajang and Jember Regencies, is one of the rivers with a risk of flooding. This is due to changes in land use and high sedimentation. For this reason, flood control efforts are needed to reduce disaster risk. This study aims to conduct flood modeling on the Jatiroto River and propose the most effective flood control. In this paper, the flood modeling uses HEC-RAS 5.0 with Q_{25y} and Q_{50y} obtained from analyzing rainfall data from 9 rainfall stations. The first modeling was carried out to produce a flow hydrograph on the upstream river section. The second modeling is carried out for the downstream river section with lateral flow on the Jatiroto tributaries. The flood modeling results show that the existing cross-sectional capacity of the Jatiroto River cannot accommodate Q_{25y}, so it overflows in several cross-sections, especially the downstream section. By normalizing the river's cross-section and constructing an embankment in the downstream area, the flow simulation results on flood modeling show that the flood discharge at 25 years and 50 years does not overflow in all cross sections. Therefore, the normalization and construction of embankments become the effective flood control option in the Jatiroto River.

1. Introduction

Rivers have a strategic role in supporting people's lives. River water is also used for domestic and industrial irrigation, fisheries, and as an environmentally friendly energy source. On the other hand, rivers have destructive power, such as floods that cause material and immaterial losses [1]. Flooding has been recognized as one of the worst disasters. It is one of the most frequent natural disasters in the world [2]. Jatiroto River is one of the rivers that often floods in the rainy season. The Jatiroto River has a strategic function, especially for the agricultural sector, namely, meeting irrigation needs in Jatiroto District and Rowokangkung District. However, the sedimentation rate of the Jatiroto River is quite high, around 256.34

m³/year [5]. Based on historical data (BPDB Lumajang), in 2018, a flood in the Jatiroto river inundated residential areas, agricultural areas, and roads. This flood causes economic loss and public health. The causes of flooding in the Jatiroto river include erosion of the retaining embankment in the downstream part of the river. The cross-sectional capacity of the Jatiroto River also decreased due to sedimentation.

To reduce the risks that arising from flooding, it is necessary to carry out flood control both structurally and non-structurally. A few studies on flood issues in Indonesia have been conducted, each considering various aspects of the problem. Some studies have researched the technical and engineering aspects of flooding, e.g., flood modeling, hazard mapping, and prediction [3]. However, these efforts are often unsuccessful due to errors in estimating river capacity and relying on a single solution. Other studies have discussed about flooding impacts, including physical damage, and economic damage [4]. Analyzing the capacity of the river with flood modeling and proposing some effective flood control alternatives is important to avoid significant failure.

Flood modeling is one of the efforts that can be made in flood control. By conducting flood modeling for discharge with certain design return periods, it is possible to find points or cross-sections that overflow [7]. HEC-RASS hydraulic is software flood modeling that has gained wider use in both the commercial and government sectors. This software is used for flood simulation, flood risk modeling and prediction, floodplain management, river system modeling, bridge and culvert design, and river channel diversion studies and simulations [6].

Based on the results of previous studies regarding 1D flow simulation for the Jatiroto River by using discharge with a 10-year return period (10_y) indicated that overflow occurred in several sections of the Jatiroto River [10]. 1D flow modeling using HEC-RAS resulted in stronger and more accurate predictions of flood flow rates than 2D flow modeling through LISFLOOD-FP and TELEMAC-2D [9]. Meanwhile, It is realized that 1D flow modeling still has limitations in visualizing the results of overflow analysis in the river area, in contrast to 2D flow modeling, which can visualize the flood inundation area [8]. The data quality strongly influences the quality of the flood modeling results, and the model applied in simulating the flood. In the context of data, in addition to rain data, river geometry data also has a big role in determining modeling accuracy [11].

This study aims to model the flood on the Jatiroto River with a flood discharge at a 25-year return period. From the results of this study, the capacity of the river needed to drain the planned flood discharge and effective flood control methods can be seen. Furthermore, river management can be carried out appropriately to overcome the risks and losses due to flooding.

2. Research Method

This research was conducted using secondary data from various institutions, such as rainfall data, flood occurrence data, river network data, and the resulting measurement data for the river topography. The research location is the Jatiroto Sub-River Basin, a part of the area of the Jatiroto River. The Jatiroto Sub-River Basin has an area of ±299.10 km^2, with the length of the Jatiroto River being ±29.30 km. The Jatiroto sub-river basin and its scheme of river networks are shown in **Figure 1**. The research design begins with the collection of primary and secondary data. Furthermore, hydrological analysis and flood modeling were carried out using HEC-RAS. After calibration, a flood model is obtained that can be used in various flood control efforts until the most optimal results are obtained.
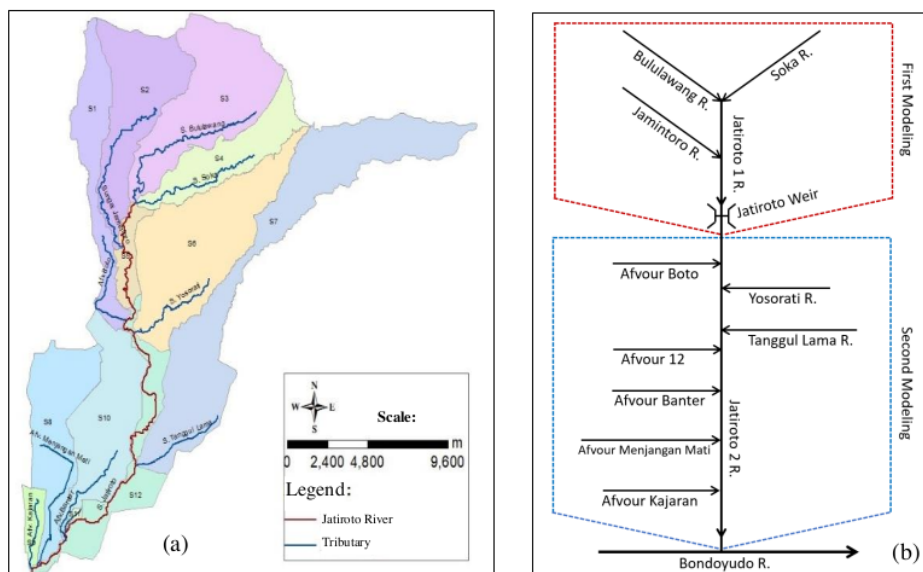
Source: Analysis Result.

Figure 1. Jatiroto Sub-River Basin and the Scheme of River Networks.

Flood modeling was conducted over the entire course of the Jatiroto River, from the upstream up to the confluence with Bondoyudo River downstream. However, the availability of data for topographical measurement results from the Jatiroto Dam to the downstream of the Jatiroto River is limited. Therefore, to determine the propagation of flooding in the downstream part, there needs to be derivative river cross-section data from DEMNAS. Flood simulation was divided into two parts: the first modeling started from the upstream of Jatiroto River to 100 m downstream of Jatiroto Dam, and the second modeling started from Jatiroto Dam to the downstream of Jatiroto River (**Figure 1b**). The first modeling was used as flood tracing so that the discharge that enters the following river section is not excessively great due to the

magnitude of the discharge from tributaries upstream. Meanwhile, the second model was used as the primary location for flood control planning. The flow simulation division aims to decrease the error value to ensure that the modeling can be stable [12].

2.1 Hydrological Analysis

a. Mean Regional Rainfall

This analysis utilized the method of Thiessen Polygons, for which the method considers the factor of the area ratio around rain stations as the representation of each of those rain stations. From this analysis, the annual maximum daily rainfall value was then obtained [13]. In this study, the daily rainfall data were taken from 9 rain stations for ten years from 2011-2020. The utilized rainfall stations were Kalipenggung, Watu Urip, Kaliboto, Rojopolo, Blimbing, Pondok Waluh, Pladingan, Pondok Joyo, and Wringin Agung.

b. Rainfall Frequency Analysis

This analysis was used to estimate rainfall amount and probability magnitude with certain return periods according to the regional rainfall. This analysis utilized the Log Pearson Type III method, where the coefficient of skewness (Cs) and coefficient of kurtosis (Ck) have the free requirement. Therefore, the Log Pearson Type III method was appropriate for all data distributions. The design rainfall is calculated by the following equation [14]:

$$\log X = \overline{\log X_i} + k \cdot Sd$$

with X = design rainfall (mm), X_i = maximum daily rainfall (mm), k = frequency factor and Sd = standard deviation.

c. Hourly Rainfall Distribution

A high rainfall intensity usually occurs with a short duration for areas that are not broad. Rainfall with high intensity, in general, rarely occurs in a broad area, but the required duration is longer [15]. This analysis utilized the Mononobe Method, for which the equation is typically used for situations of rain with a duration that is relatively short [16].

$$I_t = \frac{R_{24}}{24}\left(\frac{24}{t}\right)^{2/3}$$

with I_t = rainfall intensity (mm/hour), R_{24} = maximum daily rainfall (mm) and t = rainfall duration (hour).

d. Nakayasu Synthetic Unit Hydrograph

This synthetic unit hydrograph originates from Japan. The magnitude of the design flood discharge may be known by applying principleso the synthetic unit hydrograph, which in this case requires long rainfall data [17]. The following is the equation for the Nakayasu synthetic unit hydrograph [18].

$$Q_p = \frac{c \times A_t \times R_o}{3.6(0.3T_p + T_{0.33})}$$

with Q_p = peak of flood discharge (m^3/s), R_o = unit rainfall (mm), T_p = time from the start of rainfall to the peak of flooding (hours), A_t = river basin area (km^2) and c = flow coefficient.

2.2 Hydraulic Analysis

a. Manning's Roughness Coefficients

Differences in the roughness coefficient values for each channel cause the roughness value of a river to vary. As such, a list of Manning's roughness coefficients (n) values is created according to different materials that form channels. [19]

b. Contraction and Expansion Coefficients

Loss in energy is caused by contraction and expansion due to changes in the channel cross-section. For gradual transitions, the coefficient value is 0.1 for contraction and 0.3 for expansion [12].

c. Boundary Conditions

Two boundary conditions each at the upstream and downstream ends of a channel are needed to complete equations of dynamics and continuity, such that Q_i and y_i For $i = 1, \ldots, n$ may be calculated for each time step. The following is the equation for boundary conditions [20]:

$$\alpha \Delta y_i + \beta \Delta Q_i = \gamma_i$$

d. Unsteady Flow

The unsteady flow mathematical modeling for natural rivers can utilize equations for the law of mass and momentum conservation, which are shown as the following equations [21]:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q_l$$

$$\frac{\partial Q}{\partial t} + 2\alpha \frac{Q}{A} \frac{\partial Q}{\partial x} - \alpha \left(\frac{Q}{A}\right)^2 \frac{\partial A}{\partial x} + gA \frac{\partial y}{\partial x} + gAS_f = 0$$

Where Q = flood discharge (m^3/s), q_l = lateral discharge (m^3/s/m'), A = cross-section area (m^2), S_f = energy slope, y = flow depth (m), α = Coriolis coefficient, x = longitudinal direction (m), g = gravitational acceleration (m/s^2) and t = time (s).

e. Water Surface Profile

This analysis began by finding the relationship between the flow depth and the discharge profile. The goal is to determine the critical location points of flooding and plan dimensions for river improvement [22].

2.3   Flood Control Planning

The planning of repairs to and regulation of the river system is conducted according to the level of river development and the needs of the people. The risk of flooding may be mitigated by conducting repairs to the river to keep the river channel stable and reduce the sedimentation level[1]. The following are the types of repairs to the river:

a) River Normalization

The effort to enlarge the river's containment capacity is by normalizing the river channel. This activity aims to increase the cross-sectional capacity of the river. The factor that needs to be considered for this handling is the possibility of occurrences of erosion and sedimentation for planning a more stable river channel [23].

Activities that need to be done in river normalization includes the normalization of river cross section, improvement of river bed slope, minimizing the roughness of the river channel walls and reconstruct the hydraulics structure that is not suitable and disrupts the flood [1].

b) Embankment

The effort to mitigate floods in surrounding areas is by creating the design for an embankment to hold back floodwaters at the riverbed. Rivers that possess the criteria of having sharp curves usually will require the construction of longer embankments. Planning embankment requires the height and form of the cross-section for protection from the design flood height, which is supplemented by construction for slope revetment built according to necessity [24]. In planning the embankment, it is highly recommended to use earthfill construction by utilizing the excavation results in the river normalization work. The embankment height is calculated by considering the water surface at Q_{25y} added by the freeboard. Sosrodarsono [1] stated that the freeboard height of the embankment refers to the design flood discharge used. For a design flood of 200 to 500 m^3/s, the freeboard height is set at 0.8 m.

Determination of the slope of the embankment is related to water infiltration and the characteristics of the soil used to construct the embankment. Under normal conditions: the embankment slopes without reinforcement, and the slope of the embankment can be planned to be 1:2 or smaller. Meanwhile, the width of the embankment crest for the flood discharge of 500 to 2000 m^3/s is set at 4.0 m [1].

3. Results and Discussion

3.1   Hydrological Analysis

a. Mean Regional Rainfall

The method of Thiessen Polygons was selected as it considers the differing areas for the regions of each rain station. Based on the areas of the regions that represent each rain station, values of Thiessen Coefficients for each rainfall station were obtained. Next, the values of Thiessen Coefficients were used to calculate the mean regional daily rainfall, as shown in **Table 1**.

Table 1. Mean Regional Rainfall

Year	Mean Regional Rainfall (mm)
2011	66.60
2012	56.32
2013	64.76
2014	52.19
2015	38.75
2016	85.27
2017	49.16
2018	85.57
2019	56.95
2020	64.00

Source: Analysis Result.

According to **Table 1**, daily rainfall values ranged from 38.75 to 85.57 mm. This indicates that in the Jatiroto sub-watershed, there is heavy rain (50-100) mm.

b. Frequency analysis of design rainfall

This analysis utilized the Log Pearson Type III method, which involves the transformation of rainfall data to logarithmic values, and design rainfall with certain return periods was obtained. In the calculation of design rainfall, for the 25-year and 50-year return periods, the k values obtained are 1.70 and 1.98, respectively. Based on the frequency analysis, the values $\overline{\log X} = 1.78$ and $Sd = 0.11$ were obtained. Referring to the equation, the design rainfall for the 25-year and 50-year return periods is 91.13 mm and 97.44 mm, respectively.

c. Hourly rainfall distribution

Hourly rainfall distribution was calculated with the Mononobe Method by establishing a rainfall duration of 6 hours, adjusted to the mean duration of rainfall in Indonesia. The results of calculations for hourly rainfall distribution are shown in **Table 2**.

Table 2 shows that the maximum rain occurs in the first hour, both 25 years and 50 years of design rain. This indicates that the flood's peak will also occur in the first hour. Furthermore, the rain intensity decreased significantly at the 2nd hour and gradually until the 6th hour.

Table 2. Hourly Rainfall Distribution

Hour:	Hourly Rainfall (mm/day)	
	R_{25}	R_{50}
1	13.44	14.37
2	3.49	3.74
3	2.45	2.62
4	1.95	2.09
5	1.65	1.76
6	1.44	1.54

Source: Analysis Result.

d. Nakayasu Synthetic Unit Hydrograph

In the design flood discharge analysis, the Jatiroto River Basin is divided into 12 Sub-River Basins, and the design flood discharge value was calculated for each Sub-River Basin. Meanwhile, the peak of design flood discharge by the results of Nakayasu SUH calculations for each Sub-River Basin is shown in **Table 3**.

Table 3. Design Flood Discharge for Each Sub-River Basin

Sub River Basin	Design Peak Flood Discharge (m^3/s)	
	Q_{25y}	Q_{50y}
Jatiroto 1 River	26.60	28.18
Jatiroto 2 River	11.67	12.36
Jamintoro River	34.03	36.22
Bululawang River	44.26	47.20
Soka River	45.40	48.44
Yosorati River	78.19	83.54
Afvour Boto	107.24	114.62
Tanggul Lama River	116.98	125.03
Afvour 12	4.29	4.46
Afvour Banter	44.54	47.50
Afvour Menjangan Mati	26.60	28.24
Afvour Kajaran	8.24	8.50
Total	**584.04**	**584.29**

Source: Analysis Result.

Based on **Table 3** above. The design flood discharge for the Jatiroto River Basin is thus the sum of the discharge for each Sub-River Basin. For the return period of 25 years. The magnitude of the design flood discharge was 584.04 m^3/s. In comparison, the design flood discharge for the return period of 50 years was 584.29 m^3/s.

3.2   Hydraulic Analysis

a. Modeling of the river cross-section in HEC-RAS

Creating a hydraulic model requires river cross-section data by inputting terrain data from the Digital Elevation Model (DEM) into the RAS Mapper feature of HEC-RAS. The objective of this is to obtain data on river geometry. However, for the 1D flow modeling, the river geometry can be obtained by inputting the data between channel margins. To avoid model instability between the river cross sections that resulted from measurement and those that were derived from DEMNAS. The flow modeling was divided into two parts.

River cross-section data that utilized DEMNAS data began from the upstream of Jatiroto River to Jatiroto Dam. Meanwhile. River cross-section data that utilized survey and measurement data began from Jatiroto Dam to the downstream of Jatiroto River which is adjusted to DEMNAS.

In the previous study, one value of n (single n) was used for all river stations. While in this study for 2D modeling, the values of Manning's roughness coefficients (n) in the river channel are modified by trial and error until the inundation area, and inundation height analysis results are close to historical data. With this method, the flow depth is closer to the recorded historical data. By trial and error, the value of n is 0.025 for river sections 0-20000 and 20300-22900. As for the river section 201000-20200. the value of n is 0.023.

b. Unsteady flow analysis

For the first model, the boundary conditions of the upstream part used the flow hydrograph by inputting the design flood discharge value that had been analyzed, and the downstream part used the normal depth. In the second modeling, the boundary conditions of the upstream part used the flow hydrograph by inputting the final discharge value of the cross section resulting from the first modeling, and the downstream part used the stage hydrograph of the water surface elevation of Bondoyudo River. Meanwhile, the tributaries used lateral inflow boundary conditions by inputting the design discharge value for the tributaries that had been analyzed.

c. Flow hydrograph

The first modeling results using flood discharge with 25 years return period show that the flow hydrograph at the downstream cross-section varies every hour, as shown in **Table 4**. Next, the flow hydrograph was used as input data for the second model. While the lateral inflow uses flood hydrograph data for each sub-river basin (**Table 3**) and Stage Hydrograph as a boundary condition in the downstream part. Data on the water level of the Bondoyudo

River is used, which is 0.36 m above the water level of the Jatiroto River. The results of the water surface profile with Q_{25y} on the existing cross section are displayed in **Figure 2**.

Table 4. Flow hydrograph at the downstream cross-section of first modeling.

Hour	Q (m³/s)	Hour	Q (m³/s)	Hour	Q (m³/s)
00:00	209.02	08:00	57.36	16:00	12.47
01:00	177.04	09:00	45.17	17:00	11.17
02:00	32.19	10:00	34.31	18:00	10.16
03:00	99.69	11:00	26.95	19:00	9.31
04:00	103.65	12:00	22.09	20:00	8.64
05:00	88.82	13:00	18.54	21:00	8.10
06:00	75.57	14:00	16.01	22:00	7.66
07:00	66.11	15:00	14.09	23:00	7.31

Source: Analysis Result.

Based on the results of the HEC-RAS simulation, it was found that overflow occurred in several sections of the river, particularly in the downstream part. To obtain precise modeling results with high accuracy, 2D flood modeling was thus performed and then calibrated with the greatest height of flood inundation that had ever occurred. Results of the modeling showed that there were inundation areas due to the Jatiroto River overflow in several sections close to the tributaries. The inundation area from the simulation using HEC-RAS is shown in **Figure 3**.
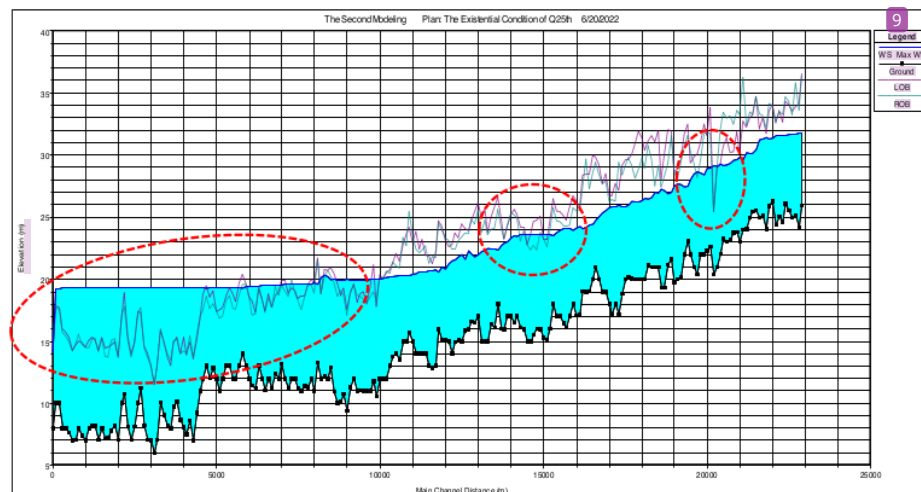
Source: Analysis Result.

Figure 2. Water surface profile on existing cross-section with Q_{25y}
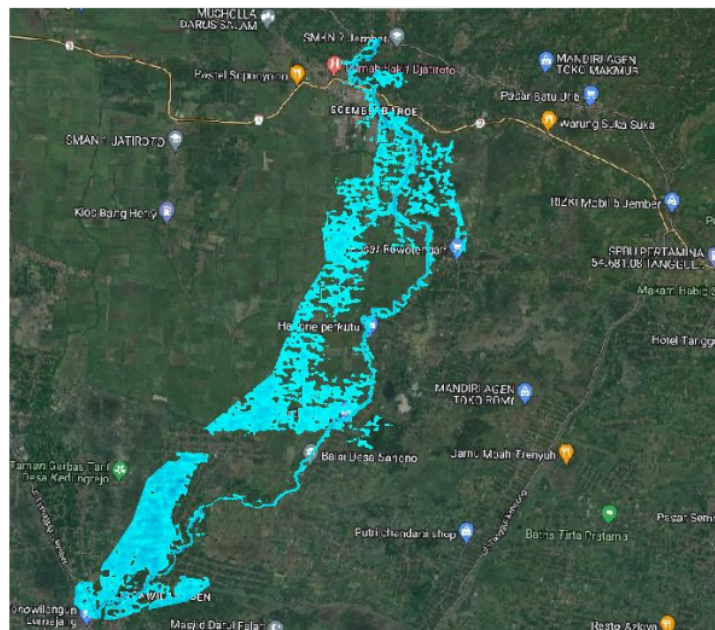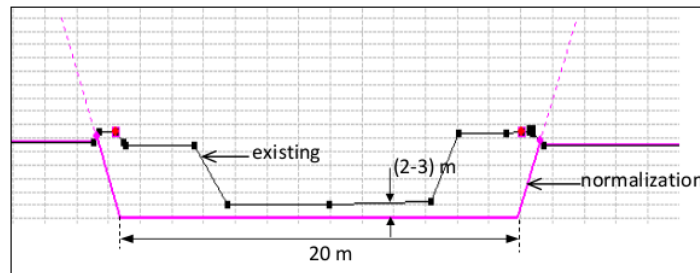
Source: Analysis Result.

Figure 3. Inundation Area from the Results for the Second Modeling with Q_{25y}

The flow simulation indicated that the cross-section of the Jatiroto River could not hold back the design flood discharge with a return period of 25y. This can be seen from the water level line above the left and right embankment lines. as shown in Figure 3 circled areas. Therefore. The problem of flooding in the Jatiroto River needs to be resolved.

3.3   Flood Control Planning
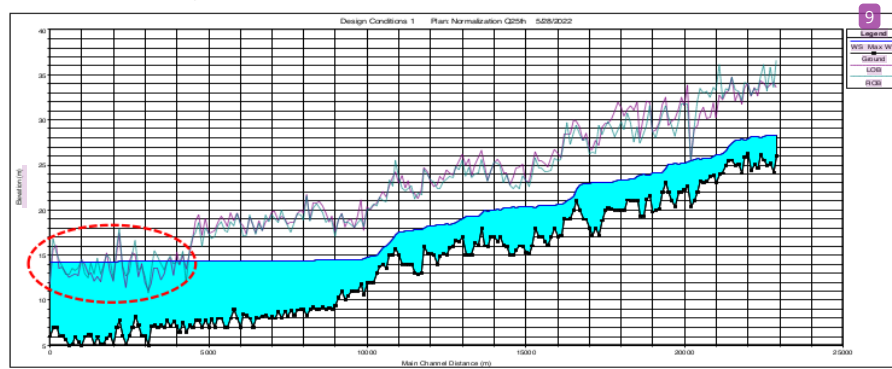
a. Normalization

One of the efforts for flood control is by conducting normalization of the river cross-section. This effort is conducted to re-optimize riverbanks' function by clearing plants, widening the river, and dredging the river bottom. In this study, the river section where normalization was conducted was from RS 0 to RS 8700 with dredging for 2 to 3 m and river widening by 20 m. This is based on the availability of the flood plain area and to maintain the flow regime or remain sub-critical flow. So that the normalization carried out does not have the potential to cause riverbed degradation in upstream. **Figure 4** shows the normalization planning for the river cross-section.

Source: Analysis Result.

Figure 4. Normalization Planning of River Cross-Section

Next. the flow simulation was conducted with HEC-RAS on the Jatiroto River that had been normalized with Q_{25y} and the results are shown in **Figure 5**.

Source: Analysis Result.

Figure 5. Water surface profile after Normalization

Based on the flow simulation results, it was found that even with flood control by normalization, overflow still occurred in several sections of the river, particularly in the downstream part. This can be seen from the water level line, which is still above the left and right embankment lines. as shown in **Figure 5** circled areas. Therefore, the next effort is the creation of an embankment becomes necessary.
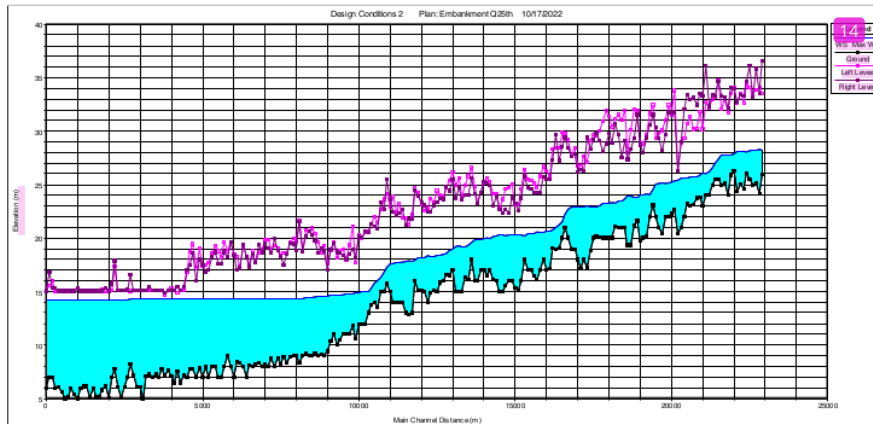
b. Embankment

In HEC-RASS, embankment elevation is the main variable that determines the capacity of a cross-section to accommodate flood discharge. The water level in a cross-section varies according to the specified simulation time [25]. From the analysis results, the design flood discharge in the study location ranged from 200-500 m^3/s, so freeboard height was planned for 0.8 m. The following are the dimensions of the embankment:

Embankment Height   : Flood water surface height + freeboard height (0.8 m)

Embankment Crest Width   : 4 m

Type of Revetment   : Earthfill construction with a slope of 1: 2

Furthermore, the flow simulation with Q_{25y} and controlled with Q_{50y} is carried out. The simulation results show no overflow along the river channel, as shown in **Figure 6**. The flood modeling results also show no change in the flow regime in the river after normalization and embankments.

Source : Analysis Result.

Figure 6. Water surface profile after normalization and embankment with Q_{25y}

4. Conclusion

Based on the hydrological analysis of the Jatiroto Sub-watershed by taking into account 12 Sub-River Basins, the design flood discharge with a return period of 25 years and 50 years is 584.03 m^3/s and 584.29 m^3/s respectively. The results of flood modeling using HEC-RAS on the existing cross and long section showed overflow in several river sections, particularly in the downstream part. For this reason, the normalization of the cross-section of the river and the addition of embankments in the downstream area were carried out. The flow simulation results on flood modeling show that the flood discharge at 25 years and 50 years does not overflow in all cross sections. Therefore, it can be concluded that these two methods, normalization and construction of embankments become an effective option in dealing with floods in the Jatiroto River.

5. Acknowledgment

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