Modeling of Flood Inundation Due to the Overflow of the Bengawan Madiun River Using HEC-HMS and HEC-RAS 2D

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Abstract

Bengawan Madiun is one of the main tributaries of the Bengawan Solo River, playing a critical role in the hydrological system of the Bengawan Solo Watershed. Limited river capacity, upstream land-use change, and increasing rainfall intensity have caused recurrent flooding in Ngawi Regency, particularly in Kwadungan and Pangkur Districts. A significant flood event occurred on 29 March 2025, inundating settlements, farmland, and infrastructure across the study area. This study aims to model flood inundation resulting from the overflow of the Bengawan Madiun River, evaluate model reliability, and analyze inundation characteristics under various return period discharge scenarios as a basis for flood mitigation recommendations. The average watershed rainfall of 72.80 mm was distributed into hourly rainfall using the Sri Harto method as input for HEC-HMS modeling. Calibration of the daily discharge model for the flood event of 29 March 2025 yielded an NSE of 0,85 and R^2 of 0,89, indicating that the model accurately represents the rainfall-runoff relationship of the Bengawan Madiun Watershed with a very high degree of accuracy. The HEC-RAS 2D simulation under existing conditions revealed a total inundation area of 6.329 km², concentrated in the lowland areas of Kwadungan and Pangkur Districts, with model validation yielding an RMSE of 0,03 m and NSE of 0,73. Return period discharge simulations demonstrated a consistent increase in inundation area from 1.654 km² at Q5 to 15.038 km² at Q50, with the 29 March 2025 flood event hydrologically identified as equivalent to a return period of 10 to 25 years. Based on these findings, river normalization and embankment construction along the critical segments of Bengawan Madiun are recommended as structural mitigation measures to significantly reduce flood inundation risk in Ngawi Regency.

Keywords: *Bengawan Madiun, Flood, HEC-RAS 2D, HEC-HMS, Inundation*

1. Introduction

Bengawan Madiun is one of the main tributaries of Bengawan Solo which is classified as a second-order river in the Bengawan Solo Watershed (DAS) system. Morphometrically, this river has a channel length of about ±141.875 km with a watershed area of ±3.750,5 km² [1]. As the main river, Bengawan Madiun plays an important role in draining discharge from the upstream area to the Bengawan Solo River. However, flood problems still often occur due to the capacity of river channels that are unable to accommodate flood discharges that pass through, causing water overflow to the surrounding area [2]. In addition to the river capacity factor, changes in land use in the upstream watershed area, which are characterized by an increase in built-up areas and a decrease in water catchment areas, as well as an increase in rainfall intensity, also contribute to an increase in surface runoff and flood discharge in the Bengawan Madiun River [3].

Kwadungan and Pangkur Districts in Ngawi Regency are areas that are often affected by floods due to the overflow of Bengawan Madiun. The geographical condition of the two sub-districts which are located in low-lying areas and adjacent to river flows causes a high level of vulnerability to flooding, especially when rain occurs with high intensity and duration. One of the flood events that occurred on March 29, 2025, the rain that lasted for four hours caused an increase in the discharge of Bengawan Madiun to exceed the capacity of the river [4]. The overflow of water that occurred inundated various areas, including roads, residential areas, and agricultural land with variations in inundation depth in the affected areas of 30-50 cm [4].

Based on these conditions, this study aims to model flood inundation due to the overflow of the Bengawan Madiun River at the flood event on March 29, 2025. Modeling was carried out through hydrological analysis to obtain flood discharge based on rainfall data at the time of the incident using a software HEC-HMS. The modeling discharge was calibrated with observational discharge data at the Ketonggo water prediction post using the Nash-Sutcliffe Efficiency (NSE) and R2 (coefficient of determination) methods [5], [6]. The discharge of the calibrated modeling results is then used as input data in two-dimensional hydrodynamic modeling using 2D HEC-RAS software. The modeling was carried out to obtain the characteristics of the flow and distribution of flood inundation in the study area. The results of inundation modeling were then validated using historical data on flood events obtained from field measurements and flood documentation [4]. The accuracy level of the model was evaluated using the statistical parameters of Root Mean Square Error (RMSE) and Nash-Sutcliffe Efficiency (NSE), so that a model capable of representing actual flood conditions with an adequate level of reliability was obtained [5], [6], [7].

2. Method

The methods used in this study include problem identification, data collection, hydrological analysis using HEC-HMS, 2D hydrodynamic analysis using HEC-RAS, spatial analysis and processing of inundation modeling results using GIS, and performance assessment of model results.

Research Location

The location of the research study focused on Bengawan Madiun from the downstream of the Bengawan Solo meeting along ±31.5 km. As a downstream of Bengawan Madiun, Bengawan Solo is limited to 1 km long model before and 1.5 km after the meeting with Bengawan Madiun. The map of the Bengawan Madiun watershed is shown in Figure 1.

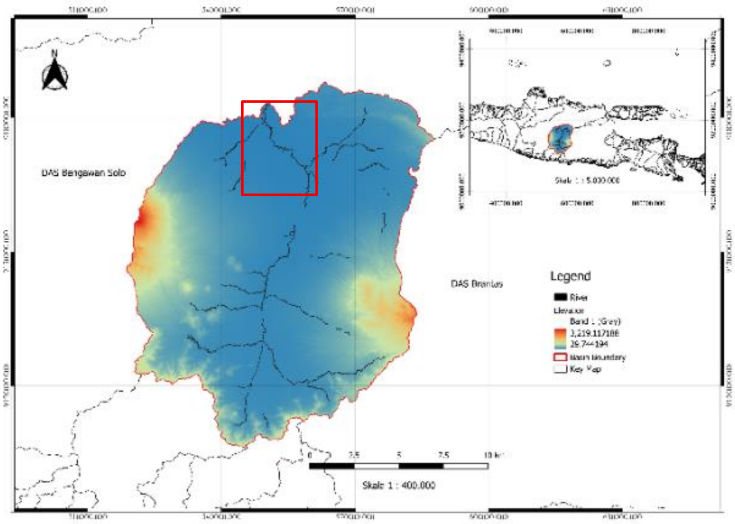


Figure 1. Bengawan Madiun Watershed

Data Preparation and Collection

The data used in this study are shown in table 1.

Table 1. Research Data

Num	Data Type	Data Source
1	Daily rainfall of rain stations in the Bengawan Madiun watershed in 2015 – 2025	BBWS Bengawan Solo
2	Water observation discharge (AWLR) in Bengawan Madiun in 2025	BBWS Bengawan Solo
3	Forset and Building Removed Copernicus DEM (FABDEM) Resolusi 30x30	https://data.bris.ac.uk/data/dataset/s5hqmjcdj8yo2ibzi9b4ew3sn
4	Land use of the Bengawan Madiun watershed in 2024	BBWS Bengawan Solo
5	Soil types of the Bengawan Madiun watershed	NASA-HYSOG https://cmr.earthdata.nasa.gov/search/concepts/C2216864285-ORNL_CLOUD.html
6	Cross section of Bengawan Madiun, ±31.5 km from downstream	BBWS Bengawan Solo
7	Bengawan Solo cross section , ± 1 km before and after the meeting with Bengawan Madiun	BBWS Bengawan Solo
8	Historical flood inundation in the Bengawan Madiun watershed in 2025	BBWS Bengawan Solo

Research Flow Diagram

The stages of the research flow in this study are shown in figure 2.

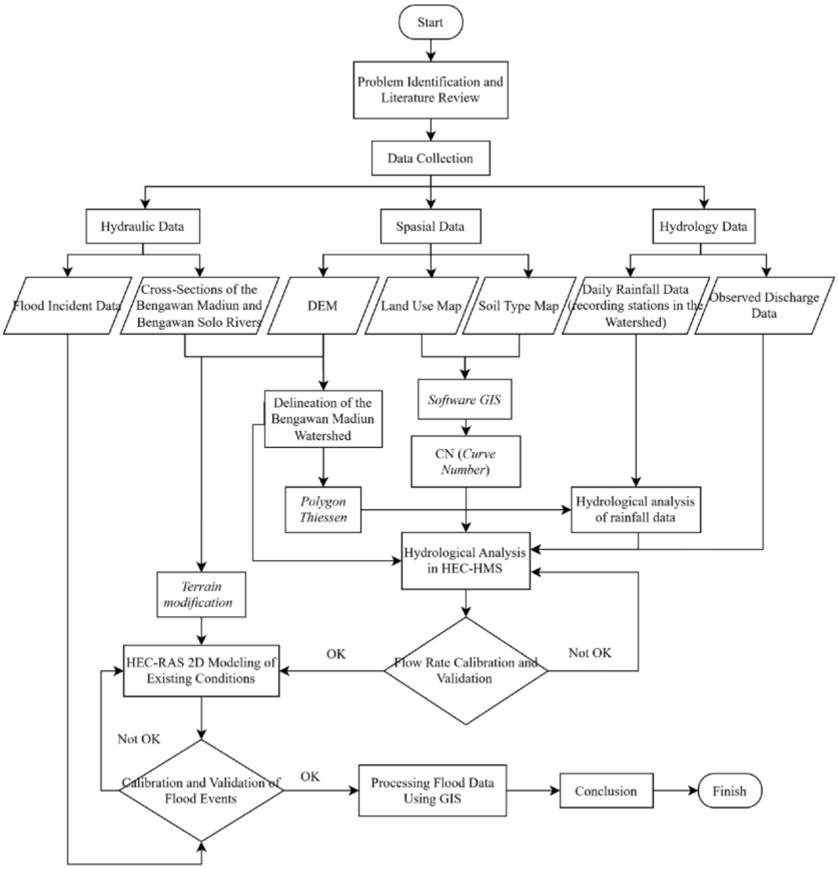


Figure 2. Research flowchart

Thiessen Polygon

The calculation of regional average rainfall is used to determine the average rainfall that occurs in the Bengawan Madiun watershed. The *thiessen polygon* method is suitable for use in areas with uneven rain stations [8]. The calculation of average rainfall in a watershed is formulated in equation (1).

$$P = \frac{P1+P2+P3+\ldots Pn}{n} \tag{1}$$

with:
A = average rainfall (mm),
$P_1, P_2, ... P_n$ = the amount of rain observed at each station (mm),
$P_1, P_2, ... P_n$ = the area of the sub-area representing each rain station (km^2).

The rain used in this calculation is the rain of flood events on March 29, 2025, from all rain stations in the Bengawan Madiun watershed.

Rainfall Distribution Hours: Sri Harto

This method explains that the variability and temporality of rainfall on the island of Java is very high, so this is an obstacle to obtaining accurate rainfall at times. From the results of research conducted by [9] The calculation of the hourly rainfall distribution is formulated in equation (2).

$$\boldsymbol{Y = -0{,}01X^2 + 2{,}14X - 10{,}38} \qquad (2)$$

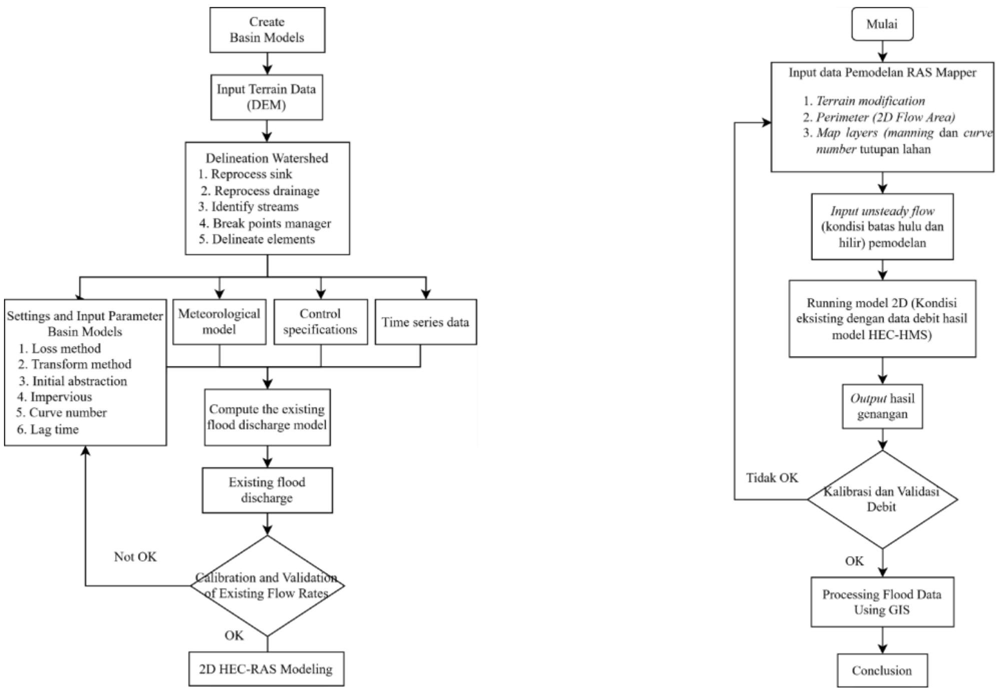
with:
Y = cumulative rainfall percentage,
X = cumulative duration percentage.

HEC-HMS Modeling

Hydrological modeling using HEC-HMS software was carried out to simulate the hydrological process, especially the relationship between rainfall and runoff in the Bengawan Madiun watershed, so that the discharge value at the time of flooding was obtained at the outlet point or review point. Detailed rain-discharge modeling flowcharts on HEC-HMS are shown in figure 3.

2D HEC-RAS Modeling

2D hydrodynamic modeling in HEC-RAS 6.7 was carried out to simulate the process of flood events in Bengawan Madiun under the conditions of existing flood events, namely March 29, 2025. The discharge data used is the result of calibrated HEC-HMS modeling. The 2D HEC-RAS modeling flowchart is shown in figure 3 (b).



(a) HEC-HMS modeling flowchart (b) HEC-RAS 2D modeling flowchart

Figure 3. HEC-HMS and HEC-RAS modeling diagrams

Model Calibration

Root Mean Square Error (RMSE)

This method measures the degree of difference between the value of the simulation result and the observation value through the square root *of the mean square error*. The simulation results are said to be accurate when the RMSE value has a value that is smaller or closer to 0 [7]. This method is calculated using equation (3).

$$RMSE = \sqrt{\left[\frac{\sum_i^n \left(Y_i^{obs} - Y_i^{sim}\right)^2}{n}\right]} \quad (3)$$

with:
Y_i^{obs} = observation data i,
Y_i^{sim} = simulation data i,
n = total amount of data.

Nash Sutcliffe Model Efficient Coefficient (NSE)

The NSE determines the relative magnitude of the residual variant compared to the measured data variant. This method indicates how well the simulation data is compared to the observation data according to a 1:1 line gradient. The simulation results can be viewed as an acceptable level of performance if they are in the range of 0 to 1 [5]. This method is calculated using equation (4).

$$NSE = 1 - \left[\frac{\sum_i^n \left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_i^n \left(Y_i^{obs} - Y_i^{mean}\right)^2}\right] \quad (4)$$

with:
Y_i^{obs} = observation data i,
Y_i^{sim} = simulation data i,
Y_i^{mean} = average data i,
n = total amount of data.

R^2 (Coefficient of Determination)

This method shows the strength of the linear relationship between the observation and simulation values by using the proportion of the total variance in the observed data. The value ranges from 0 to 1, a higher value means the model performs better [6]. This method is calculated using equation (5).

$$\boldsymbol{R^2} = \left[\frac{\sum_i^n \left(Y_i^{obs} - \underline{Y}_i^{obs}\right)\left(Y_{simi} - \underline{Y}_{sim,i}\right)}{\sqrt{\sum_i^n \left(Y_i^{obs} - \underline{Y}_i^{obs}\right)^2 * \sum_i^n \left(Y_{simi} - \underline{Y}_{sim,i}\right)^2}}\right]^2 \quad (5)$$

with:
Y_i^{obs} = observation data i,
$\underline{Y}_i^{obs}$ = average observation data,
Y_i^{sim} = simulation data i,
$\underline{Y}_i^{sim}$ = average simulation data.

3. Results and Discussion

Regional Average Rainfall Analysis

The extent of the influence of rain stations was obtained from the analysis of voronoi polygon in QGIS software. The value of the area of influence will be multiplied by the value of rainfall to get the weighted rainfall value. The results of the calculation of the thiessen polygon rainfall on March 29, 2025 in the Bengawan Madiun watershed are shown in Table 2.

Table 2. Results of the calculation of the average rainfall of the thiessen polygon

Num	Rain Station	Wide Influence	Rainfall	Rainfall Weighted
		%	mm	mm
1	Waduk Sangiran	3,03%	36	1,09
2	Waduk Pondok	3,60%	56	2,02
3	Karangsari	1,86%	46	0,85
4	Jururejo	7,10%	82	5,81
5	Kedungbrubus	3,10%	51	1,58
6	Notopuro	3,68%	70	2,58
7	Madiun - Jiwan	12,69%	99	12,56
8	Dawuhan	6,55%	72	4,72
9	Jatirogo	6,31%	54	3,41
10	Telaga Negebel	6,52%	72	4,70
11	Purwantoro	7,70%	74	5,70
12	Gonggang	12,66%	83	10,51
13	Bangunsari	11,64%	75	8,73
14	Sooko	6,02%	39	2,35
15	Slahung	7,53%	82	6,18
	Total	100%		72,80

From the calculation results, the average rainfall value of the watershed was 72,80 mm. The rainfall value will be distributed into rain hours as an input time *series* of rain data in HEC-HMS to obtain a discharge value at the time of flooding.

Analysis of the Distribution of Rainfall Hours by the Sri Harto Method

The average rainfall value calculated in table 1 is distributed into the rain hours of the Sri Harto method using equation (2) with a rainfall duration of 4 hours [4]. In addition to the value of flood rain, the rain distributed includes rain for the 5, 10, 25, and 50 yr return period. The results of the hourly rainfall distribution are shown in table 3.

Table 3 Distribution of rainfall hours March 29, 2026, R2, R5, R10, and R50 yr

Duration of Rain	Percentage	R March 29, 2025 (mm)	Return Period (year)			
hour	%		R5 yr (mm)	R10 yr (mm)	R25 yr (mm)	R50 yr (mm)
1	35,58%	25,904	23,752	25,744	28,122	29,810
2	33,54%	24,414	22,387	24,264	26,505	28,096
3	21,47%	15,632	14,334	15,536	16,971	17,990
4	9,41%	6,850	6,281	6,808	7,437	7,883
Total	100%	72,800	66,754	72,351	79,036	83,780

The rain distribution on March 29 was used to obtain the results of inundation of existing conditions on that date, while the rainfall value of the R5, R10, R25 and R50 year rain distribution was used to obtain the discharge value of the return period. The rain distribution value is used as an input for rain parameters in HEC-HMS.

HEC-HMS Modeling Analysis

HEC-HMS modeling is carried out by modeling discharge based on rain data input that occurs in the Bengawan Madiun watershed. The watershed delineation point is the same as the location of the Ketonggo AWLR point. The location is a record or observation of discharge which is used as a calibration and validation value for modeling discharge. The results of watershed delineation using the outlet point or breakpoint of AWLR Ketonggo were obtained as shown in figure 4.

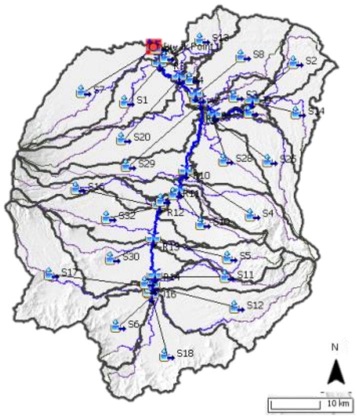


Figure 4. Bengawan Madiun watershed model basin with breakpoint on AWLR Ketonggo

Based on figure 4, the results of the watershed delineation will be obtained from the value of watershed characteristics such as the area and slope of the sub-basin or sub-basin, as well as the length and slope of the river channel. The parameters required in modeling include curve number, initial abstraction, % impervious, lag time, and base flow. These parameters will be optimized until the results of the discharge modeling are close to the Ketonggo AWLR observation discharge [10]. Discharge modelling was carried out using regional average daily rainfall data from February 15 to July 13, 2025 as shown in figure 5.

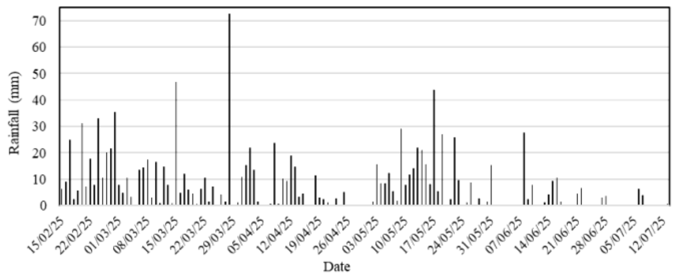


Figure 5. Average daily rainfall for the region from February 15 to July 13, 2025

Calibration HEC-HMS Discharge Modeling

The calibration of the initial model was carried out by modeling rainfall series data from February 15 to July 13, 2025 (figure 5). The data is used to facilitate parameter optimization. The results of the discharge modeling will be calibrated by observation of the discharge of the Ketonggo water suspected post on that date. If the calibration with the data series has been met, it will be continued for the input of rain distribution data on March 29, 2025. The calibration process was carried out using the optimization test feature on HEC-HMS to optimize the values of curve number, initial abstraction, impervious, and lag time parameters. The results of calibrated discharge modeling are obtained in figure 6.

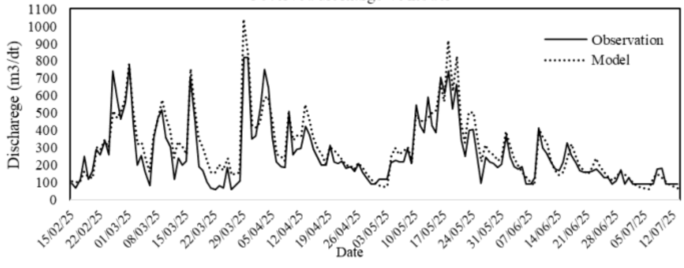


Figure 6. Calibration results of modeling discharge with observational discharge (AWLR Ketonggo)

From the results of the model calibration, the curve number parameter optimization value was obtained with a value range of 63,685 – 76,086; initial abstraction value 15,967 – 28,966; and impervious value of 2% – 55,63%. Meanwhile, the lag time reach value was obtained from the upstream point to the Ketonggo water suspected post for 3.918,3 minutes or 63,305 hours. The results of model performance in figure 6 are obtained using the NSE and R^2 methods as shown in table 4.

Table 4. Value of model calibration and validation results

Method	Value	Performance Category
NSE	0,85	Excellent
R^2	0,89	Excellent

After parameter calibration is carried out and the results of the model performance in the good category are obtained, the data from the calculation of the rain distribution of the Sri Harto method in figure 5, is entered into the calibrated model to obtain the hourly discharge value on March 29, 2025 and the discharge of the Q5, Q10, Q25, and Q50 return periods of the year. The discharge results will be used as *boundary conditions* or upstream boundary conditions in 2D hydrodynamics modeling. The results of discharge modeling on Bengawan Madiun and the 31.5 km segment tributaries from the downstream of the Bengawan Solo meeting are shown in figure 7 and figure 8.

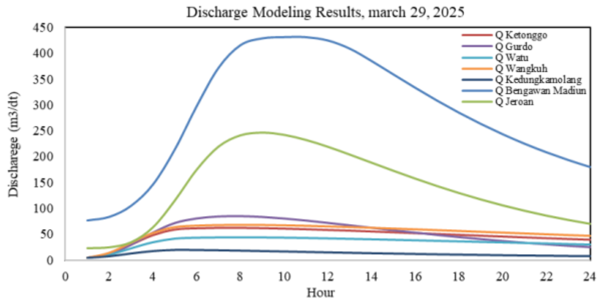
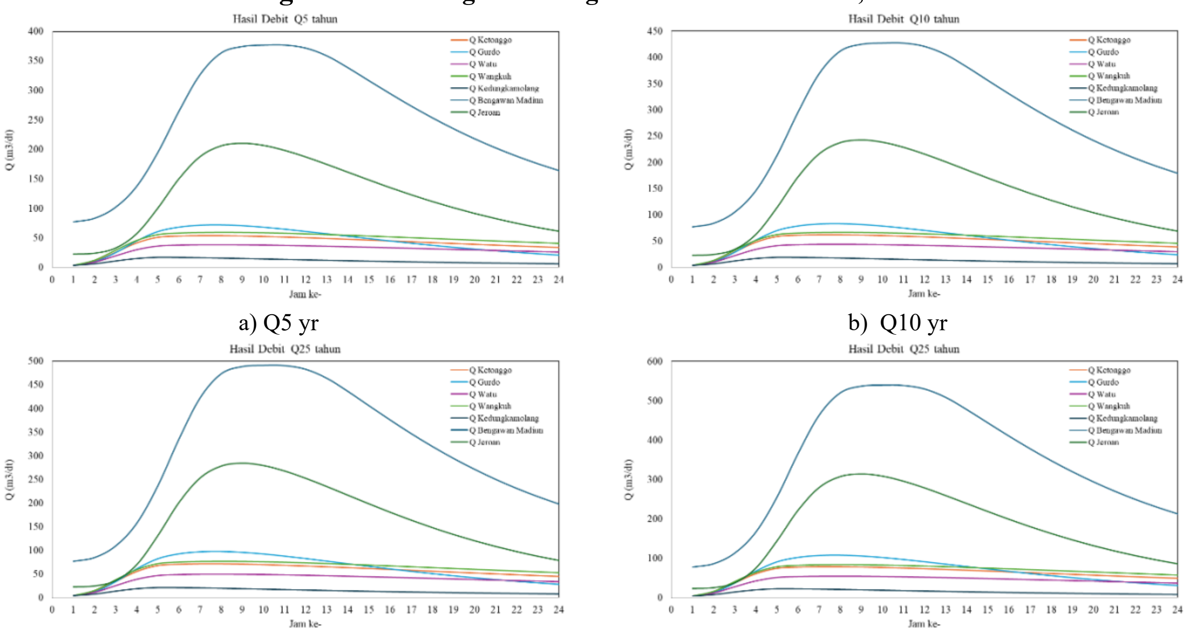


Figure 7. Discharge modeling results as of March 29, 2025



a) Q5 yr

b) Q10 yr

c) Q25 yr

d) Q50 yr

Figure 8 Results of return period discharge modeling

2D HEC-RAS Hydrodynamic Analysis

Hydraulic modeling was carried out using HEC-RAS 2D software to simulate the flow characteristics and distribution of flood inundation in the confluence area of the Bengawan Madiun and the Bengawan Solo. The model was created based on a combination of ground surface topographic data obtained from the FABDEM with a resolution of 30x30 [11], [12] As well as data from field surveys in the form of cross *sections* and *long* sections of rivers. The modeled river section includes the ±31.5 km long Bengawan Madiun which is calculated from the mouth of its confluence with the Bengawan Solo River. In addition, the model also includes Bengawan Solo along ±1 km upstream and ±1 km downstream from the meeting point, as well as several tributaries directly connected to the Bengawn Madiun river system. The geometry of the two-dimensional area (2D *Flow Area)* was carried out using RAS 2025 alpha. The size of the mesh in the longitudinal direction is set at 20 m, while in the horizontal direction (*width*) the parameter *count* of 10 cells is used. Meanwhile, in the floodplain area and land cover around the river, a *triangular* type *mesh* with an element size of 30 m is used [13]. The *boundary condition* in the upstream part of each river is determined using *a flow hydrograph*. The boundary condition in the downstream part of the model is determined using *normal depth* with an energy slope value of 0.0006. Schematic image of the model shown in figure 9.

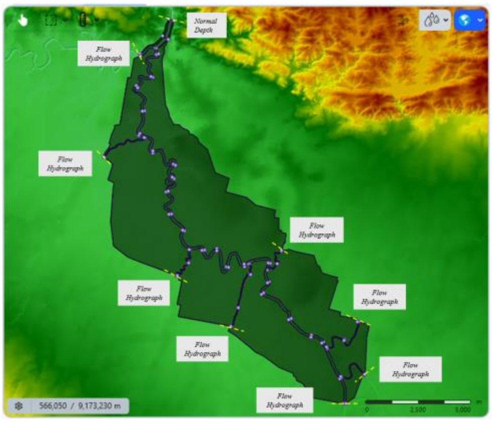


Figure 9. Skematik model HEC-RAS 2D

Results of HEC-RAS 2D Flood Inundation Modeling

The results of the HEC-RAS 2D hydrodynamics model simulation at the March 29, 2025 flood event showed that the distribution of inundation was concentrated in the lowlands around the Bengawan Madiun River channel, especially in the Kwadungan and Pangkur sub-districts. The results of the flood modeling simulation are shown in figure 10.

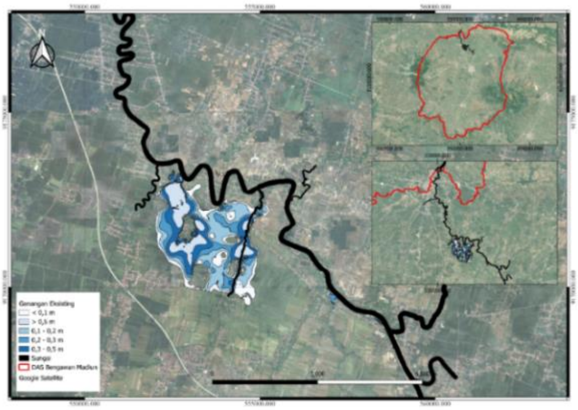


Figure 10. Inundation modeling results on March 29, 2025

Based on existing inundation maps, inundation distributions are classified into five depth classes [14]. The results of the HEC-RAS 2D simulation on the March 29, 2025 flood event showed a total inundation area of 6,329 km², concentrated in lowlands in Kwadungan and Pangkur Districts. The 0,1–0,2 m depth class dominated the inundation area of 1,783 km² (28,2%), followed by the less than 0,1 m class covering an area of 1,342 km², the 0.2–0.3 m class covering an area of 1,097 km², the more than 0,5 m class covering an area of 1,072 km², and the 0,3–0,5 m class covering an area of 1,035 km². An even pattern of inundation distribution across all depth classes indicates that the overflow covers multiple topographic zones simultaneously, with the deepest inundation (> 0,5 m) concentrated in the topographic basin zone in the central part of the affected area. The results of the inundation depth comparison model were compared with data from inundation depth measurements in the field. The calibration points of the model used were 6 depth measurement points at the time of the flood on March 29, 2025 based on the measurement results and some news from the news. The results of the comparison are shown in table 5.

Table 5. Calibration of inundation models with flood event recording data

Num	Observation points	Depth of observation (m)	Model depth (m)	Differences (m)
1	Waruk Kalong village, Kwadungan district	0,5	0,54	0,04
2	Dinden village, Kwadungan district	0,35	0,32	-0,03
3	Purwosari village, Kwadungan district	0,4	0,44	0,04
4	Pojok village, Pangkur district	0,35	0,31	-0,04
5	Simo village, Kwadungan district	0,3	0,29	-0,01
6	Tirak village, Kwadungan district	0,4	0,42	0,02

The performance of the results was carried out using the RMSE and NSE methods. The results of the model performance calibration are shown in table 6.

Table 6. Results of the model calibration assessment

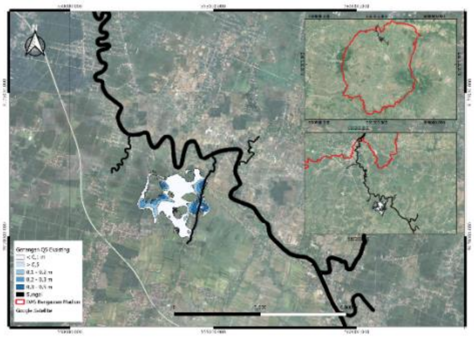
Method	Value	Performance Category
NSE	0,73	Good
RMSE	0,03	Excellent

The parameters that are optimized include manning landcover and curve number. A recap of the parameters that have been optimized and some input parameters in the HEC-RAS 2D map layer are shown in table 7.

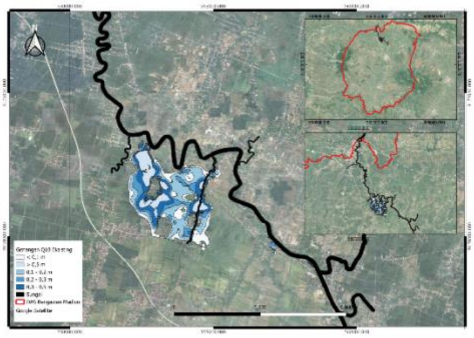
Table 7. HEC-RAS recap calibrated input parameters

Num	Land Cover	n Manning	% Impervious	CN	Abstraction Ratio	Minimum Infiltration Rate
1	Water bodies	0,033	0%	100	0	0
2	Secondary Dryland Forest	0,100	3%	78,008	0,200	0,300
3	Mixed Dryland Agriculture	0,040	10%	87,657	0,200	0,300
4	Rice Fields	0,038	15%	88,838	0,150	0,100
5	Open Ground	0,030	3%	93,790	0,100	0,100
6	Bushes	0,065	7%	75,037	0,200	0,300
7	Settlement	0,060	60%	88,556	0,050	0,000
8	Dryland Agriculture	0,040	7%	87,779	0,200	0,300
9	Airport/Port	0,016	90%	91,451	0,050	0,000
10	Plantation Forest	0,080	3%	79,091	0,200	0,300
11	Mining	0,018	45%	93,511	0,100	0,000
12	Plantation	0,055	10%	80,453	0,200	0,300

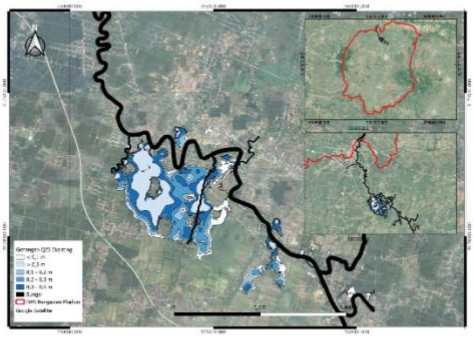
To analyze the characteristics of inundation in various hydrological scenarios, advanced simulations were carried out using planned flood discharge with repeat periods of Q5, Q10, Q25, and Q50 years as the input of HEC-RAS 2D modeling. In Q5 yr, the total inundation area of 1,654 km² was confined to the riverbank zone, indicating that the rivers holding capacity has not been significantly exceeded. In Q10 yr, the inundation area increased significantly to 5,100 km² (an increase of 208% compared to Q5), indicating a threshold effect that caused massive overflows into the lowlands. In Q25, the inundation area reached 9,957 km², exceeding the existing condition by 57,3%, with significant spatial expansion towards settlements and infrastructure in Kwadungan and Pangkur Districts. In Q50, the total inundation area reached 15,038 km² or 137,6% wider than the existing conditions, with a depth class of more than 0.5 m reaching 3,752 km² (24,9% of the total inundation).The results of the Q5, Q10, Q25, and Q50 yr modeling are shown in figure 11.



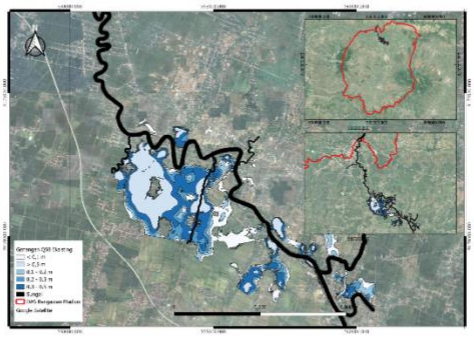
a) Inundation modeling results Q5 yr



b) Inundation modeling results Q10 yr



c) Inundation modeling results Q25 yr



d) Inundation modeling results Q50 yr

Figure 11. Discharge inundation results for the return period of Q25 and Q50 yr

The results of the recapitulation of the extent of inundation of existing conditions on March 29, the discharge conditions of the Q5, Q10, Q25, and Q50 yr are presented in table 8 and figure 12.

Table 8. Depth and area of inundation with discharges dated March 29, Q5, Q10, Q25, and Q50 years

Number	Depth	Inundation Area (km²)				
		Q March 29, 2025	Q5 yr	Q10 yr	Q25 yr	Q50 yr
1	0 - 0,1 m	1,342	0,802	1,325	1,818	2.828
2	0,1 - 0,2 m	1,783	0,418	0,822	1,562	2.225
3	0,2 - 0,3 m	1,097	0,248	0,982	2,180	2.931
4	0,3 - 0,5 m	1,035	0,153	0,995	1,987	3.301
5	> 0,5 m	1,072	0,033	0,978	2,409	3.752
Total		6,329	1,654	5,100	9,957	15,038

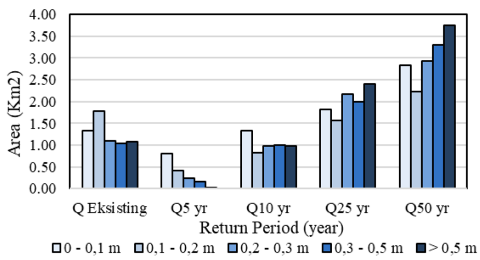


Figure 12. Depth and area of inundation with discharges dated March 29, Q5, Q10, Q25, and Q50 yr

Based on a comparison between the area of the existing inundation (6,329 km²) and the simulation results of Q10 (5,100 km²) and Q25 (9,957 km²), the flood event on March 29, 2025 was hydrologically identified as equivalent to a repetition period of between 10 to 25 years. These findings indicate that the flood control infrastructure in the study area needs to be designed to be able to accommodate discharges with a recharge period of at least 25 years.

4. Conclusion

The calibration of the HEC-HMS model at the March 29, 2025 flood event resulted in an NSE value of 0,85 and an R^2 of 0,89, indicating that the model is able to represent the rain-runoff relationship of the Bengawan Madiun watershed with an excellent level of accuracy. The HEC-RAS 2D simulation showed a total area of 6,329 km² of inundation concentrated in the lowlands of Kwadungan and Pangkur Districts, with model validation resulting in an RMSE value of 0,03 m and an NSE of 0,73. Simulations of re-period discharge showed an increase in inundation area from 1,654 km² in Q5 to 15,038 km² in Q50, with the identified March 29, 2025 flood event equivalent to a 10- to 25 year return period. The normalization of river flows and the construction of embankments in the critical segment of Bengawan Madiun are recommended as structural mitigation efforts to reduce the risk of flooding in Ngawi Regency.

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