Hydrodynamic Modelling of Juwana River Flooding Using HEC-RAS 2D

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Abstract. On the equator, Indonesia had very complex geographical, geological, hydrological conditions. It was also traversed by three large plates namely the Eurasian plate, the Indo-Australian plate, and the Pacific plate. Because of the colliding meeting of the three plates, the territory of Indonesia had a variety of topography ranging from hills, mountains, plateaus, lowlands, and basins. The basin found in the Juwana watershed caused frequent flooding every year due to the overflow of Juwana River. The river passed through Kudus and Pati. In the last ten years there had been 179 floods in Juwana River. This study aimed to examine the discharge and distribution of floods based on the return period of floods 2, 5, 10, 25, 50, and 100 years. The research method used was frequency analysis, snyder synthetic unit hydrograph analysis, and hydrodynamic model using HEC-RAS 5.0.6 2D (two dimension) with unsteady flow. The findings indicated that on the return period of floods 2, 5, 10, 25, 50, and 100 years, the discharge and distribution of floods were 1169.2 m³ with the inundated area of 22898.54 Ha, 1401.7 m³ with the inundated area of 25558.51 Ha, 1541 m³ with the inundated area of 26916.42 Ha, 1704.9 m³ with the inundated area of 28411.52 Ha, 1819.9 m³ with the inundated area of 29905.85 Ha, and 1930 m³ with the inundated area of 30785 Ha respectively.

1. Introduction
A flood can be defined as a massive water flow exceeding the river capacity. Consequently, the water overflows and inundates flood plains or other plains bordering with the main river [8]. Flood striking the Indonesian territories cannot be separated from the watershed. Watershed is a plain area with a complex hydrology unit holding, storing, and flowing the rainwater to be drained to the lake and sea [6]. The area should be properly managed to reduce the impacts of disaster and flood strikes.

Juwana watershed is one of the watersheds in Central Java. It administratively covers Pati and some areas in Kudus. It obtains a national priority to be handled [3]. The area of Juwana watershed is 1368 km², dominated for agriculture interests. The floods striking Pati and Kudus have reportedly led to a significant loss in agriculture sectors, especially in paddy. Every year, most floods strike during the rainy season. The lack of public knowledge concerning the disaster makes the impact even greater [1].

To reduce the impact and avoid the flood strike, a right and integrated flood control system plan is necessary, one of that is by using hydrodynamic modeling and simulation. Today, hydrodynamic modeling allows a complex model, hence a faster and more accurate analysis [11].

Hydrodynamic modeling integrated with Geographic Information System (GIS) will help the public mitigate disaster and improve public attention to an impending disaster in their areas [12]. Besides, it also helps predict the loss caused by the flood. Therefore, the development performed can be more effective.

2. Study Area and Materials

2.1 Study Area
Astronomically, Juwana watershed is located between 6°37’53.89” latitude to 6°59’36.788” latitude and 110°46’7.983” east longitude to 111°14’3.504” east longitude with total area of 1368 km². Observed from the administration border, it is located in Pati, Kudus, and a small area of Grobongan and Blora in Central Java. Juwana watershed is presented in Figure 1.
Figure 1. Location of Juwana Watershed

Juwana watershed is located in the basin area and most of the area is in the lowlands, especially the middle to downstream area. The highest elevation of this watershed is 1400 m above the sea level and the lowest elevation is 0 m above the sea level. The slope of Muria Mountain and Kapur Mountains, the plateau areas are only in the east and south parts. The main river in this watershed, Juwana River has a length of 62 m. Its upstream is in Kudus; while the downstream is in Pati.

2.2 Data Sources
The research analyzed the return period of floods 2, 5, 10, 50 and 100 years in Juwana River. It implemented a hydrodynamic modeling to find the distribution and discharge of flood in Juwana River using HEC-RAS 5.0.6 software. Data consisted of primary and secondary data. Primary data were collected using field observation technique and interview; while the secondary data were collected by institutional survey. The secondary data used were 8.1 m resolution DEMNAS data, rainfall data with the length for 28 years, administrative map and land use map, and land type map.

3. Methods
Hydrodynamic modelling was performed using 2D (two dimensions) analysis requiring several data to produce more accurate flood inundation mapping [13]. Research flowchart was presented in Figure 2.

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**Figure 2. Research Flowchart**

Hydrological Data

- Regional Rainfall
- Frequency Analysis
- Effective Rainfall
- Distribution of Hourly Rainfall

Synthetic Unit Hydrograph

Cook Coefficient (c)

- Type of Soil
- Land Use
- Topography

Hydrodynamic Model

HEC-RAS 5.0.6

DEM

Geometric Extract

Creating 2D Flow Area

Generating 2D Mesh

Boundary Condition

Unsteady Flow Data

2D Unsteady Flow Analysis

Validation

Flood Inundation
Several methods as shown in the research flowchart were conducted to achieve more optimal research results. Firstly, accurate hydrology data were required to model a flood. In this research, daily rainfall data with the length of 28 years were needed; while the frequency was analyzed to find rainfall values according to return periods. Next, effective rainfall was calculated by multiplying Cook coefficient value (c) by the return period. Parameters to find the value referred to the soil type map, land coverage, slope, and low density. After that, hourly rainfall was calculated and used as the input for synthetic unit hydrograph calculation. The synthetic unit used was snyder – alexeyev. Output found was in the form of flood discharge and hydrograph data. The flood discharge was used as the input for the hydrodynamic model. The modeling used HEC-RAS 5.0.6 software with a 2D model. In addition to discharge, elevation model data should also be extracted into geometric data. 2D area was made to design the flood distribution and depth. 2D area consisted of mesh and was used for the condition limit, where the upper limit was the input point for the river discharge and the lower limit was for tidal data [14]. For the flood inundation data, we used 2D unsteady flow analysis. The flood inundation model was validated following the flood in the field. The validation was performed using the Root Mean Square Error (RMSE) method.

4. Results and Discussion

4.1 Regional Rainfall Analysis

Regional rainfall was calculated using Polygon Thiessen method. The method was developed by an American meteorology expert, Alfred H. Thiessen. It was to find the regional rainfall distribution based on raindrop points within the coverage of each raindrop point forming a polygon [5].

Figure illustrates Thiessen Polygon distribution in Juwana watershed. Thiessen distribution used maximum daily rainfall data, with the data length of 28 years (1991-2018) and 12 rain stations spread over Juwana watershed.

4.2 Frequency Analysis

Frequency analysis, testing, and determination of frequency distribution types were performed to calculate the designed rainfall. The calculation of maximum daily rainfall was also performed to determine the designed rainfall in a particular return period. Frequency analysis was widely known as the basic analysis to determine the probability of the amount of rainfall based on the available data statistic [2].
Maximum daily rainfall data were used to measure dispersion. The dispersion measurement could be done using several types of frequency distribution i.e. Normal, Gumbel, Log-Normal, and Log Pearson III Distributions [15]. Statistical parameters measured were mean, standard deviation (S), Kurtosis Coefficient (Ck), Skewness Coefficient (Cs), and Variation Coefficient (Cv). Methods for probability testing performed in this research were chi-square and Smirnov Kolmogorov. Based on the testing, the best distribution was logged normally as seen in Table 1.

| No. | Type of Distribution | Chi-Square Value | Critical Chi-Square Value | Smirnov-Kolmogorov Test | Critical Smirnov-Kolmogorov Value |
|-----|----------------------|------------------|---------------------------|------------------------|----------------------------------|
| 1   | Normal               | 8.857            | 7.815                     | 0.106                  | 0.248                            |
| 2   | Gumbel               | 7.571            | 7.815                     | 0.154                  | 0.248                            |
| 3   | Log Normal           | 5.429            | 7.815                     | 0.143                  | 0.248                            |
| 4   | Log Pearson III      | 8.000            | 5.991                     | 0.117                  | 0.248                            |

Log normal was used to calculate the return periods of designed rainfall that were T 2, 5, 20, 25, 50 and 100 years with the minimum rainfall of return period of two years was 100.548 mm and maximum rainfall of return period of 100 years was 152.54 mm. The results are indicated in Table 2.

| Probability P(x >= Xm) | Return Period T | Rainfall Characteristics According to Its Probability XT (mm) | KT |
|------------------------|-----------------|---------------------------------------------------------------|----|
| 0.5                    | 2               | 100.548                                                      | -0.103 |
| 0.2                    | 5               | 120.536                                                      | 0.831 |
| 0.1                    | 10              | 132.520                                                      | 1.391 |
| 0.04                   | 25              | 146.614                                                      | 2.049 |
| 0.02                   | 50              | 156.506                                                      | 2.511 |
| 0.01                   | 100             | 152.549                                                      | 2.326 |

4.3 Flow Coefficient

The value of runoff coefficient strongly affected flood discharge. The rainfall runoff directly flowing on an area provided either fast or slow flow when leading to drainage channel that later would go to primary channel or river, depending on the land use around the channel [16]. The value of the coefficient could also be used to determine physical condition of a watershed, whether or not it had a good physical condition. It was in line with Kodoatie and Syarief [4] stating that the value of runoff coefficient was one of the indicators to determine physical conditions of a watershed. The range of C value was between 0 - 1. If C = 0, all rainwater was interrupted and filtrated into the soil and vice versa. While C =1, all rainwater flowed as runoff.
Regarding Cook coefficient, some parameters from watershed were used to calculate the value of runoff coefficient of Juwana watershed. The parameters were slope, land coverage, soil infiltration, and flow density (Figure 4). The value of runoff coefficient was found by scoring each parameter and performing overlay from the four parameters. The values of overlay aggregate and Cook coefficient (c) can be seen in Table 3.
Table 3. The Value of Overlay Aggregate

| No. | Overlay Aggregate | Area (Km²) | \((b/\sum b \cdot a)\) |
|-----|-------------------|------------|----------------------|
| 1   | 30                | 0.20       | 0.00                 |
| 2   | 25                | 0.04       | 0.00                 |
| 3   | 35                | 5.44       | 0.14                 |
| 4   | 70                | 99.24      | 5.08                 |
| 5   | 55                | 134.58     | 5.41                 |
| 6   | 45                | 61.38      | 2.02                 |
| 7   | 50                | 70.03      | 2.56                 |
| 8   | 40                | 18.99      | 0.56                 |
| 9   | 65                | 83.10      | 3.95                 |
| 10  | 75                | 155.44     | 8.52                 |
| 11  | 60                | 61.76      | 2.71                 |
| 12  | 80                | 444.13     | 25.98                |
| 13  | 85                | 182.67     | 11.35                |
| 14  | 100               | 22.30      | 1.63                 |
| 15  | 95                | 17.60      | 1.22                 |
| 16  | 90                | 10.63      | 0.70                 |
|     | Total             | 1368       | 72                   |
|     | Cook Coefficient  | 0.72       |                      |

The value of Cook coefficient was 0.72. It indicated that 72% of rainwater flowing to Juwana watershed system became runoff; while 28% was infiltrated into soil.

4.4 Effective Rainfall

Before the designed rainfall was modeled as runoff, the value of effective rainfall from the rainfall entering the watershed system should be assessed. The effective rainfall was calculated by multiplying the designed rainfall by Cook coefficient (c). Then the effective rainfall was transformed into hourly rainfall using ABM (Alternating Block Method) method and Mononobe formula [17]. Meanwhile, the hourly calculation was conducted using Kirpich formula. The result of hourly rainfall distribution with the return period can be seen in the Table.

Table 4. Distribution of Effective Rainfall with Return Period

| Hour | Return Period | 2   | 5   | 10  | 25  | 50  | 100 |
|------|---------------|-----|-----|-----|-----|-----|-----|
| 1    |               | 5.2 | 6.2 | 6.8 | 7.6 | 8.1 | 8.6 |
| 2    |               | 6.1 | 7.4 | 8.1 | 9.0 | 9.6 | 10.1|
| 3    |               | 42.3| 50.8| 55.8| 61.7| 65.9| 69.9|
| 4    |               | 11.0| 13.2| 14.5| 16.0| 17.1| 18.2|
| 5    |               | 7.7 | 9.3 | 10.2| 11.3| 12.0| 12.7|

4.5 Synthetic Unit Hydrograph

Snyder synthetic unit hydrograph was added Alexeyev equation to find the hydrograph curve. Moreover, to investigate the distribution of effective rainfall based on its return period, we used superposition hydrograph. Then, the peak discharge in each return period of flood was found as follows: 1169.2 m³/second in the return period of flood 2 years, 1401.7 m³/second in the return period of flood 5 years, 1541 m³/second in the return period of flood 10 years, 1704.9 m³/second in the return period of flood 25 years, 1819.9 m³/second in the return period of flood 50 years, and 1930 m³/second in the return period of flood 100 years.
4.6 2D Hydrodynamic Modelling

We used HEC-RAS 5.0.6 software for our hydrodynamic modelling. Developed by US Army Corp of Engineers (2002), the software was able to model flood inundation area well [18].

Flood inundation modelling was conducted using 2D (two dimensions) unsteady flow analysis. The model emphasized unsteady flow from the upstream part (the initial stage of modelling) to the lower stream (the end/finishing stage of modelling) due to various and unsteady river flow [9]. In 2D modelling of HEC-RAS, the cross section function was substituted by 2D mesh containing elevation and manning information in each grid and cell faces [7]. 2D mesh created was then added the boundary conditions. The upper boundary was the data of flood flow discharge calculated using HSS Snyder-Alexeyev; while the lower boundary was the tidal data collected from BBWS Pemali-Juwana. The current HEC-RAS 5 was able to create a 2D flood model up to a maximum mesh size of 1×1 m/cell. However, we needed a digital elevation model from the result of LIDAR processing or terrestrial measurement to obtain the mesh [7]. Input required to do hydrodynamic modelling using HEC-RAS was DEM data, Flood Hydrograph Data, and Manning’s Roughness Value. The last Value was obtained from the land use map of Juwana watershed as indicated in table 5 and figure 6.

| No. | Name                       | Manning’s Value |
|-----|----------------------------|-----------------|
| 1   | Lake                       | 0.035           |
| 2   | Rain-fed rice field        | 0.023           |
| 3   | Shrub                      | 0.1             |
| 4   | River                      | 0.035           |
| 5   | Empty/infertile land       | 0.035           |
| 6   | Field                      | 0.035           |
| 7   | Reservoir                  | 0.035           |
| 8   | Pond                       | 0.035           |
| 9   | Building                   | 0.3             |
| 10  | Jungle                     | 0.16            |
| 11  | Meadow                     | 0.1             |
| 12  | Salting                    | 0.035           |
| 13  | Plantation                 | 0.035           |
| 14  | Settlement                 | 0.1             |
| 15  | Rain-fed rice field        | 0.023           |
Figure 6. Manning’s Roughness Map of Juwana Watershed
4.7 Flood Inundation

Based on the result of flood inundation modelling using 2D HEC-RAS, the flood inundation in the return period 2, 5, 10, 25, 50, and 100 years was 22898.54 Ha, 25558.51 Ha, 26916.42 Ha, 28411.52, 29905.85 Ha, and 30785.75 Ha respectively.

![Flood Inundation Modelling](image)

**Figure 7.** Result of Flood Inundation Modelling in the Return Periods

4.8 Model Validation

Flood inundation models were validated by comparing the modelling result with the field measurement result. Sampling was conducted based on the flood height found by observing the flood track. The track was investigated by interviewing people staying near the sampling location. Sampling location and interview with people nearby are presented in Figure 8 and Figure 9. The level of model accuracy towards the actual condition was measured using RMSE regarded as a standard vertical accuracy test.
on spatial data [10]. The RMSE value of a flood model was 0.37. It indicated that the model was acceptable with the value of less than one.

![Model Validation sample points](image1.png)

**Figure 8.** Model Validation sample points

![Interview and field validation](image2.png)

**Figure 9.** Interview and field validation
According to the interview result, flood striking the areas along Juwana River occurred almost every year whenever the rainy season came. Based on the model validation, modeling the 100-year return period with the altitude value and the distribution of flood inundation is the same as the January - February 2014 flood event. It meant that flood striking the areas along Juwana River in 2014 came with a discharge of 1930/second with the flood area of 30785.75 Ha.

Several respondents clarified that flood inundation stayed for one weak-one month. The inundation had interrupted their activities, making them suffer from loss, especially in the agricultural sectors. Interestingly, the respondents also confirmed that tidal flood also stroke during the dry season. The seawater would flow through the river, making farmers unable to use the water to irrigate their land.

5. Conclusion
By the modelling, the amount of peak discharge and flood inundation area in return periods of flood 2, 5, 10, 25, 50, and 100 years was 1169.2 m³/second and 22898.54 Ha, 1401.7 m³/second and 25558.51 Ha, 1541 m³/second and 26916.42 Ha, 1704.9 m³/second and 28411.52 Ha, 1819.9 m³/second and 29905.85 Ha, and 1930 m³/second and 30785.75 Ha respectively. Due to the wide flooded area and its massive impact, further management should be conducted in Juwana watershed. The floods occur due to sloping and relatively flat areas, causing prolonged inundation. In addition to further management, normalization should also be conducted in Juwana River. In conclusion, predicting a more accurate peak flow discharge requires sufficient data and automatic discharge recording using AWLR tool, enhancing the recording accuracy. HEC-RAS 5.0.6. Hydrodynamic modelling had been able to model flood inundation. Meanwhile, the capability greatly depended on the hydrological analysis and DEM resolution. The higher the DEM resolution, the better the way to represent flood that occurs in the field.

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