Estimating design flood and HEC-RAS modelling approach for flood analysis in Bojonegoro city

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Abstract. Bojonegoro faces flood every year with less advanced prevention development. Bojonegoro city development could not peak because the flood results material losses. It affects every sectors in Bojonegoro: education, politics, economy, social, and infrastructure development. This research aims to analyse and to ensure that river capacity has high probability to be the main factor of flood in Bojonegoro. Flood discharge analysis uses Nakayasu synthetic unit hydrograph for period of 5 years, 10 years, 25 years, 50 years, and 100 years. They would be compared to the water maximum capacity that could be loaded by downstream part of Bengawan Solo River in Bojonegoro. According to analysis result, Bengawan Solo River in Bojonegoro could not able to load flood discharges. Another method used is HEC-RAS analysis. The conclusion that shown by HEC-RAS analysis has the same view. It could be observed that flood water loading is more than full bank capacity elevation in the river. To conclude, the main factor that should be noticed by government to solve flood problem is river capacity.

1. Introduction
Flooding is one of the most happening hazards worldwide, including Indonesia. Flood disaster happens frequently when wet season comes to Indonesia. Flood problems make material losses and cause discomfort social activities. They affect to the low city development in every sectors. Flood could be derived from natural factors and due to human activity itself. Each year, national media reported that flood disasters’ result was dramatically increased from previous flooding.

When the wet season approaches to Indonesia, several prevention acts are well planned. But, nature has more destructive power. Schanze (2006), Nyarko (2000), and Merz et al. (2007) concluded that flooding is the undesired rise of water level either by dam failure or long rainfall duration with high intensity. The most popular region with both drought and flood disasters is Bojonegoro. Bojonegoro is located in the downstream of Bengawan Solo River, East Java. It could not be denied that in the past several years, Bojonegoro suffered drought in dry season with minimum availability of water. However, abundant water is found in wet season in the form of flood hazard. In the beginning year of 2017, flooding in Bojonegoro destructed 203 houses and affected over 1100 people. Some experts argued that the factors due to overflowing river, poor drainage system, ecological destruction, forest clearing both legally and illegally, or river capacity are several answers for ‘what is the main reason of
flood in Bojonegoro?” question. Furthermore, this research aims to prove one of those well-known factors: river capacity.

Hydrologic models are used to simulate peak runoff and design storm hydrographs. There are several methods to compute runoff in a watershed. Nigussie (2015) proposed Snyder’s, Soil Conservation Service, Mockus, Nakayasu, Rodriguez-Valdez, and Gupta-Waymire synthetic unit hydrograph (SUH) to seek peak runoff. Models such as the Rational method, USDA Soil Conservation Service (SCS) method, and Nakayasu method have been widely used in practice to estimate peak runoff in Korean watersheds (Jung and Moon, 2001). Furthermore, Kang (2009) advised five different models, including Rational, WFRP, Nakayasu, SCS, and Clark methods to estimate peak discharges.

Rivera (2007) conducted and performed a study of hydrological modeling to determine potential regions to be flooded during high rainfall events in the Aguán river basin, Central Honduras. This procedure was made by using HEC-RAS model (Hydrological Engineering Center-River Analysis System). Final result demonstrated the exact location of areas with high, moderate, and low risk to be flooded in specific high flood events. Paringit (2015) used HEC-RAS to reach periodic outflow while considering surface roughness to generate flood extents.

2. Methodology

To prepare the study of flood analysis, methods that could help this research steps are systematically needed. Firstly, literature study is conducted from various journals, feasibility study reports, research reports, government regulations, and other publications. This research uses secondary data. Hydrological data are obtained from Balai Besar Wilayah Sungai Bengawan Solo. This research assumes each river cross sections have same characteristics as trapezoidal channel. Lack of primary and secondary data availability about river cross sections makes HEC-RAS analysis is difficult to obtain the best result.

According to the availability data, two stages of methods analysis would be conducted in this research, namely the analysis of design peak runoff using Nakayasu synthetic unit hydrograph and the simulation using HEC-RAS software. The research aims to compare flood loading with river capacity. Manning’s equation helps this research to analyze river capacity. The analysis using HEC-RAS modeling goals to determine hazard area, to obtain runoff height information, and to show the cross sections characteristics of Bengawan Solo River downstream.

3. Results and Discussion

3.1. Analysis of flood

Bengawan Solo River flows into Bojonegoro district, in East Java province. It is classified in the Sub-basin Bengawan Solo downstream area. Bengawan Solo River divides 2307.06 hectares area of Bojonegoro into two areas with 0-8% slope interval. It is located in low land with elevation of +12.00 m until +15.00 m. Based on the topography, Bojonegoro district in northern part is lower than the southern part. Therefore, all of the streams flow to the estuary in the northern part of Bengawan Solo River. Based on hazard data from Regional Disaster Management Agency of Bojonegoro, 146 villages in 16 districts were frequently hit by flood due to overflowing of Bengawan Solo River.

3.1.1. Thiessen polygon analysis. Generally, hydrological analysis is one part of the preliminary analysis to design hydraulic structures. Hydrological analysis is required to determine the characteristics of hydrology from Bengawan Solo river basin to Bojonegoro City. Hydrological analysis is used to determine the volume of designed flood discharges. Point of origin derives from the flood-impacted region from Bengawan Solo Basin Main Office data. Geographic Information System (GIS) analysis results that the location of this research watershed total area has 11,056.71 km². Downstream part of Bengawan Solo River length is approximately 315,099 m. Figure 1 shows the
flood-impacted region in 2016. This data is managed by Balai Besar Wilayah Sungai Bengawan Solo. Figure 2 depicts GIS user interface result for Bengawan Solo watershed that used in this research.

Figure 2. GIS analysis of Bengawan Solo watershed

### 3.1.2. Distribution compatibility test

This analysis is conducted in Normal, Log-normal, Gumbel, and Log Pearson type-III. Both Squared-chi and Smirnov-kolmogorov test result that all of those distributions meet satisfying result. The result of squared-chi test for those distributions are 1.33, 1.33, 3.00, and 0.5, respectively. They are less than the critical value: 5.99. Furthermore, Smirnov-Kolmogorov results 0.091, 0.116, 0.161, and 0.099, respectively. They are less than the critical value: 0.380. The analysis of GIS is not only for calculating areas, but also finding the run off coefficient. In this research, the weighed coefficient is computed for return period of 5-year, 10-year, 25-year, 50-year, and 100-year. The coefficients are 0.3306, 0.3541, 0.3925, 0.4259, and 0.4667, respectively. Furthermore, these coefficients could be brought to acquire flood discharges.

| Year | Yogyo | Semarang | Sawahan |
|------|-------|----------|---------|
| 2004 | 106   | 85       | 102     |
| 2005 | 98    | 98       | 165     |
| 2006 | 131.5 | 152      | 77      |
| 2007 | 117.8 | 108      | 150     |
| 2008 | 102   | 119      | 215.5   |
| 2009 | 85    | 235      | 180     |
| 2010 | 131   | 139      | 156     |
| 2011 | 81    | 106      | 182     |
| 2012 | 118   | 110      | 123     |
| 2013 | 131.3 | 146.5    | 128     |
3.1.3. Nakayasu synthetic unit hydrograph. This synthetic unit hydrograph method formula as written in the equation 1, aims to find the return period discharges. Table 2 and figure 3 show the amount of peak discharges estimation that chanced in each return period.

\[
Q_p = \frac{C.A.Ro}{3.6(0.3T_p + T_{0.3})}
\]  

(1)

![Bengawan Solo watershed flood hydrograph](image)

**Figure 3.** Bengawan Solo watershed flood hydrograph

| Year | Rain gauge station | Yogya | Semarang | Sawahan |
|------|--------------------|-------|----------|---------|
| 2014 |                    | 85.3  | 141.7    | 147.5   |
| 2015 |                    | 73.9  | 71       | 130     |

### Table 2. Runoff Estimation Analysis

| Return Period (years) | Peak runoff (m³/s) |
|-----------------------|--------------------|
| 5                     | 3750.98            |
| 10                    | 4242.70            |
| 25                    | 4969.26            |
| 50                    | 5579.20            |
| 100                   | 6297.57            |

3.2. River capacity analysis

According to the simulated discharge data in table 2, the comparison analysis with the maximum capacity of river to load up water discharge is conducted. The river capacity is analysed with Manning equation (Chow, 1959). Equation 2 figures the formula to calculate Manning coefficient. In addition, the simulated river design has 180 m base width, slope of 0.00017, \( z = 1 \), and \( n = 0.03 \). The maximum daily height in the downstream part of Bengawan Solo River is 10 m (Kurniawati, 2016) and the result of maximum projected water loading of the river is approximately 3605.1352 m³/s.
\[ Q = A \times R^{2/3} \times S^{1/2} \times n \]  

(2)

Based on the calculation and the comparison analyses, Solo River downstream area could not accommodate the existing overflow. So, when rainfall experiences return period discharge of 5-year, 10-year, 25-year, 50-year, and 100-year, flood would happen. The result could be observed in the table 3.

| H (m) | A (m$^2$) | P (m) | R (m) | V(m/s) | Q storage (m$^3$/s) |
|-------|-----------|-------|-------|--------|---------------------|
| 10    | 1900.00   | 208.2843 | 9.1221 | 1.8974 | 3605.1352          |
| 9.5   | 1800.25   | 206.8701 | 8.7023 | 1.8388 | 3310.2400          |
| 9     | 1701.00   | 205.4558 | 8.2792 | 1.7787 | 3025.5063          |
| 8.5   | 1602.25   | 204.0416 | 7.8526 | 1.7107 | 2751.1091          |
| 8     | 1504.00   | 202.6274 | 7.4225 | 1.6537 | 2487.2387          |
| 7.5   | 1406.25   | 201.2132 | 6.9889 | 1.5887 | 2234.1026          |
| 7     | 1309.00   | 199.7990 | 6.5516 | 1.5217 | 1991.9286          |
| 6.5   | 1212.25   | 198.3848 | 6.1106 | 1.4526 | 1760.9673          |
| 6     | 1116.00   | 196.9706 | 5.6658 | 1.3813 | 1541.4969          |
| 5.5   | 1020.25   | 195.5563 | 5.2172 | 1.3074 | 1333.8273          |
| 5     | 925.00    | 194.1421 | 4.7646 | 1.2306 | 1138.3074          |
| 4.5   | 830.25    | 192.7279 | 4.3079 | 1.1507 | 955.3333           |
| 4     | 736.00    | 191.3137 | 3.8471 | 1.0671 | 785.3601           |
| 3.5   | 642.25    | 189.8995 | 3.3821 | 0.9792 | 628.9182           |

3.3. **HEC-RAS analysis**

Another proposed method to analyze the factor of flood is performed by using HEC-RAS software. The procedure in using this program are (a) entering the river geometric data, (b) entering steady flow data, and (c) entering return period discharge. The lack of cross sections data in this river makes the result could not create excellent performance. This research assumes that all of the cross sections in this river have the same patterns. The river base level starts at 0 meter and full bank elevation plus surveillance height reaches 13.33 meters. However, this analysis result makes the previous discussed method stronger. According to HEC-RAS analysis, it could be noticed that point in the downstream (sta.0), flood discharge is still under the maximum capacity. But, in the central point (sta.49), design peak runoff with return period of 25, 50, and 100 years begin to overspill. Furthermore, the upstream point (sta.98), all of return periods’ flood discharge experience spilling over. The expected location of simulated points are reserved in figure 5. The samples of river’s cross sections test result by using HEC-RAS could be comprehended in figure 4 and table 4.
Figure 4. Cross sections of downstream part of Bengawan Solo River from HEC-RAS analysis.
Table 4. HEC-RAS cross section result in Sta.98, Sta.49 and Sta.0

| Sta. of River | Return period (years) | Peak runoff (m³/s) | Runoff level (m) | Velocity (m/s) | Discharge level (m) |
|--------------|-----------------------|--------------------|-----------------|---------------|-------------------|
| 98           | 5                     | 3750.98            | 13.85           | 1.23          | -0.52             |
| 98           | 10                    | 4242.70            | 14.50           | 1.30          | -1.17             |
| 98           | 25                    | 4969.26            | 15.41           | 1.39          | -2.08             |
| 98           | 50                    | 5579.20            | 16.11           | 1.46          | -2.78             |
| 98           | 100                   | 6297.57            | 16.89           | 1.54          | -3.56             |
| 49           | 5                     | 3750.98            | 12.07           | 1.59          | 1.26              |
| 49           | 10                    | 4242.70            | 12.74           | 1.69          | 0.59              |
| 49           | 25                    | 4969.26            | 13.65           | 1.71          | -0.32             |
| 49           | 50                    | 5579.20            | 14.29           | 1.80          | -0.96             |
| 49           | 100                   | 6297.57            | 14.99           | 1.90          | -1.66             |
| 0            | 5                     | 3750.98            | 3.74            | 5.86          | 9.59              |
| 0            | 10                    | 4242.70            | 4.05            | 6.09          | 9.28              |
| 0            | 25                    | 4969.26            | 4.48            | 6.39          | 8.85              |
| 0            | 50                    | 5579.20            | 4.83            | 6.62          | 8.50              |
| 0            | 100                   | 6297.57            | 5.23            | 6.86          | 8.10              |

4. Conclusion
To conclude, the flood in Bojonegoro city is caused by the water loading capacity of the river could not accommodate all of the simulated design peak runoff. The HEC-RAS software analysis agrees that the flood water level from all of simulated design peak runoff is more than full bank elevation of Bengawan Solo River in Bojonegoro City. So, Bojonegoro government should concern to this factor to reduce flood problems’ impacts in Bojonegoro City. This research suggests deeper analysis about HEC-RAS river cross sections with detailed primary data to get more comprehensive and better result.

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