Flood hydrograph simulation to estimate peak discharge in Ciliwung river basin

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Abstract. Ciliwung River Basin is one of 13 watersheds located in the Special Capital Region of Jakarta (DKI Jakarta), one of the most vulnerable cities facing flood disaster. Modeling hydrographs in a flood computer model is a crucial process in understanding the hydraulic processes in floods; however, more often than not, there are not adequately studied watersheds. Well-calibrated hydrographs serve as the basis for a basin-wide flood model. In this study, the Snyder, ITB, and SCS Unit Hydrograph are constructed in the study case of flooding in the Ciliwung River Basin, with West Java rainfall distribution method and Alternating Block Method as the adopted rainfall distributions, providing six combinations of approaches. Calibration and validation analysis show a combination of West Java rainfall distribution and SCS UH with a lag time of 5.5 gives the smallest deviation, with an accuracy of 83.3%, therefore it is recommended for use to estimate design future flood hydrograph.

1. Introduction
Ciliwung River Basin is one of the 13 watersheds located in the Special Capital Region of Jakarta (DKI Jakarta), the government, and the national capital of Indonesia. The Ciliwung watershed has an elongated watershed area of 337 square kilometers with about 117 kilometers-long main river, starts from Bogor regency down into the Java Sea. Along with Krukut River and Baru Barat River, Ciliwung forms the West Flood Canal (Kanal Banjir Barat) system, which covers 28% of the total area of Jakarta. Jakarta is the city with the largest population in Southeast Asia, with a population of more than 10 million and growth reaching 0.94% annually [1], caused by high fertility rate and regional migration. High flow rates on the Ciliwung River, which flows through the center of Jakarta, regularly cause major flooding during the rainy season [2]. Flooding is considered one of the biggest problems facing Jakarta today; it is considered as one of the most vulnerable cities facing flood disaster [3], [4], primarily due
to land subsidence and land use change [5], [6]. Floods in 2007 were classified as national disasters with losses reaching 5.2 trillion rupiahs (US$ 360 million), of which 74% of total losses occurred in residential areas [7]. In 2013, Jakarta experienced another major flood, where 124 villages were submerged with a total of 20 fatalities. The floods in 2013 are estimated to cause losses of 7.5 trillion rupiahs (US$ 520 million). In addition to causing damage to the area around the river, flooding in the Ciliwung watershed also had a direct impact on several vital national objects, including the National Monument (Monumen Nasional) and the presidential palace of the Republic of Indonesia. Non-structural measures, such as hazard mapping and flood risk, can be very effective for land use planning and flood damage mitigation [8].

Based on the area distribution, the Ciliwung watershed is divided into 3 regions, upstream, middle, and downstream. As a system, changes that occur in the upper reaches of the river area will affect the entire watershed [9]. In analyzing the effects of flooding, the generating flood model is a crucial process [10] but the uncertainty of the intensity of rain events that will occur in the future can cause significant errors. To minimize errors that occur, it is necessary to determine the type of rainfall distribution that is suitable for the simulation [11], [12], [13]. In addition to determining the distribution of rain that occurs, determining the unit hydrograph in the hydrological model also greatly affects the output of the flood simulation. In hydrological modeling, a watershed is treated as a number of small homogeneous units to overcome spatial heterogeneity resulting from the variability of physical processes and physical characteristics in watersheds. Spatial discretization must be detailed enough to get results as realistic as possible, while at the same time it should be as simple as possible to shorten the modeling time and can be modeled with limited data [14]. Not all hydrograph units provide satisfactory results for each watershed due to many variables taken into account, especially in determining the response time [15], [16].

The purpose of this study is to determine the type of rainfall distribution and unit hydrograph suitable for use in flood model simulations in the Ciliwung watershed. Rain distributions that will be compared are West Java Trend (WJT) and Alternating Block Method (ABM), while the hydrograph units that will be compared are the Snyder, ITB, and SCS unit hydrograph. The determined combination of rain distribution and hydrograph unit can be used as a reference in analyzing the predictions of flooding that occur in the future. In this research, HEC-HMS will be used as a hydrological modeling tool to generate flood hydrographs at Depok stream gage, where the Depok sub-watershed covers more than 73% of the total Ciliwung watershed as an important key in the management of DKI Jakarta’s flood prevention and mitigation.

2. Materials and methods

2.1. Study area

Jakarta is located around 6°12'S and 106°48'E, in lowland are with an average altitude of 7 meters. Jakarta consists of 662.33 km² land and 6,977.5 km² ocean and has more than 110 islands located in Seribu Regency and around 27 rivers/canals. Around 40% of the DKI Jakarta Province area is in the form of plains whose land surface is 1-1.5 meters below the tidal sea level and around 3% of the DKI Jakarta Province area is relatively flat. The upstream part of the Ciliwung River is the Bogor watershed, with an area of 230 km², altitude ranging from 338 m to 2,982 m, a steep slope of 8-15% in the Bogor and Cibinong regions, and more than 15% in the Ciawi-Puncak area. The regional geology structure of the Jakarta area consists of Pleistocene deposits located around 50 meters below ground level. On the northern side, the hard soil layer is found at a depth of 10-25 meters, while further to the south, the hard soil layer is shallower at depth of 8-15 meters. Figure 1 shows the study area.
2.2. Rainfall intensity
The hourly rainfall intensity data is crucial to determine the land response in the form of flood runoff hydrograph for calibration analysis and hydrological validation. In some cases, however, where there is no measurement data for hourly rain intensity, the intensity will be approached by distributing daily rainfall into hourly data based on historical characteristics of rain. The duration of rain that occurs falls into 4 categories according to the amount of daily rainfall that occurs [11], as can be seen in Table 1.

Table 1. West Java rainfall duration.

| Catchment | Rainfall Duration  | 50 – 75 mm | > 75 mm | > 100 mm | > 150 mm |
|-----------|--------------------|------------|---------|----------|----------|
| 1         |                    | 4          | 4       | 7        | 4        |
| 2         |                    | 5          | 6       | -        | 5        |
| 3         |                    | 5          | 6       | 7        | 6        |
| 4         |                    | 4          | 5       | 4        | 4        |
| 5         |                    | 6          | 6       | -        | 6        |
| **Average** |                | **4.8**    | **5.4** | **6**    | **5**    |

Table 2. Comparison of alternating block method and West Java trend rainfall distribution.

| Time | Alternating Block Method | West Java Trend |
|------|--------------------------|-----------------|
| 1    | 18.0  11.5  8.5  6.8  5.6  4.8  68.0  26.0  11.0  12.0  50.5  12.3 | 18.0  11.5  8.5  6.8  5.6  4.8  68.0  26.0  11.0  12.0  50.5  12.3 |
| 2    | 69.3  63.0  15.2  10.0  7.6  6.1  24.0  61.0  54.0  54.0  25.5  50.2 | 69.3  63.0  15.2  10.0  7.6  6.1  24.0  61.0  54.0  54.0  25.5  50.2 |
| 3    | 12.6  16.4  58.5  55.0  13.6  9.1  8.0  10.0  28.0  24.0  12.6  4.4 | 12.6  16.4  58.5  55.0  13.6  9.1  8.0  10.0  28.0  24.0  12.6  4.4 |
| 4    | 0  9.1  10.7  14.3  52.3  50.0  0  3.0  6.0  6.0  6.5  7.7 | 0  9.1  10.7  14.3  52.3  50.0  0  3.0  6.0  6.0  6.5  7.7 |
| 5    | 0  0  7.2  8.0  9.5  13.0  0  0  1.0  3.0  3.4  21.5 | 0  0  7.2  8.0  9.5  13.0  0  0  1.0  3.0  3.4  21.5 |
| 6    | 0  0  0  5.9  6.4  7.3  0  0  0  1.0  1.2  2.4 | 0  0  0  5.9  6.4  7.3  0  0  0  1.0  1.2  2.4 |
| 7    | 0  0  0  0  5.0  5.4  0  0  0  0  0.3  1.2 | 0  0  0  0  5.0  5.4  0  0  0  0  0.3  1.2 |
| 8    | 0  0  0  0  0  4.4  0  0  0  0  0  0.3 | 0  0  0  0  0  4.4  0  0  0  0  0  0.3 |

There are several methods to transform daily rainfall into hourly intensity rainfall, including Alternating Block Method and observation at the past record. Chow et al. [17] proposed a simple method called Alternating Block Method (ABM). The design hyetograph produced by this method specifies the
precipitation depth occurring in n successive time intervals of duration Dt over a total duration nDt. The total precipitation over time is calculated and the nDt precipitation is known by the difference between successive precipitation depth. The maximum intensity is placed in the center hyetograph and the remaining lower blocks arranged in descending order to the right and left of it. Through historical rain data, it is concluded that the distribution of rainfall intensity in the province of West Java followed a trend based on the length of the rain that occurred, ranging from 3 to 8-hour rainfall [14]. Alternating Block Method and West Java trend rainfall distribution can be seen in Table 2.

2.3. Snyder unit hydrograph
Snyder (1938) was the first to propose a unit hydrograph technique that could be used on ungauged basins. His method was based on a number of watersheds in the Appalachian Highlands, ranging in size from 10 mi$^2$ to 10,000 mi$^2$ [18].

\[ t_L = Ct (L . Lc)^n \]  

\[ T_p = t_L + 0.5 t_r \]  

where:
\( t_L \) = lag time (hour)
\( L \) = length of the main stream from the outlet to the divide (km);
\( Lc \) = length of the main stream to the nearest watershed (km);
n and \( Ct \) = lag time coefficient;
\( T_p \) = time to peak (hour); and
\( t_r \) = rainfall duration (hour).

With peak discharge defined as:

\[ Q_p = 2.083 C_p \left( \frac{A}{T_p} \right) \]  

where:
\( Q_p \) = peak discharge (m$^3$/s);
\( C_p \) = peaking coefficient; and
\( A \) = watershed area (km$^2$).

2.4. Institut Teknologi Bandung unit hydrograph
Institut Teknologi Bandung (ITB) unit hydrograph is a unit hydrograph developed from Snyder UH in the Indonesian regions. ITB UH calculation requires relatively few watershed data and forms a relatively simple unit hydrograph curve, but the results are quite accurate as reflected by the ratio of runoff to rainfall intensity close to 100 percent [19].

\[ t_L = C t \ 0.81225 \ L^{0.6} \]  

\[ T_p = t_L + 0.5 \ t_r \]  

\[ Q_p = \frac{1}{3.6 \ T_p} \ \frac{A_{WS}}{A_{SUH}} \]  

where:
\( A_{WS} \) = watershed area (km$^2$); and
\( A_{WS} \) = UH area (dimensionless).
2.5. Soil conservation service unit hydrograph

Soil Conservation Service (SCS) unit hydrograph is a common method used to predict runoff from certain rainfall events, it is relatively simple but well-established because the required data is easily obtained, well documented, and considers various factors that influence runoff generation and combine them into one single parameter [20]. The SCS-CN method is based form calculating runoff from rainfall depth:

\[
Q = \frac{(P - I_a)^2}{(P - I_a) - S}
\]

where:
- \(Q\) = direct runoff (mm);
- \(P\) = rainfall (mm);
- \(S\) = potential maximum retention (mm); and
- \(I_a\) = initial abstraction (about \(I_a = 0.2S\))

Potential maximum retention defined by CN:

\[
S = \frac{25400}{\text{CN}} - 254
\]

Lag time approached by:

\[
t_L = \frac{L^{0.8}(2540-22.86 \text{CN})^{0.7}}{14104 \text{CN}^{0.7}I^{0.5}}
\]

With peak discharge as:

\[
Q_p = U_p A Q F_p
\]

where:
- \(L\) = river length (km);
- \(I\) = riverbed slope (m/m');
- \(A\) = watershed area (km²);
- \(Q\) = discharge (mm); and
- \(F_p\) = lake/swamp calibrating factor.

The peak of the unit hydrograph that occurs with the SCS method is:

\[
U_p = C \frac{A}{I_p}
\]

where \(C\) = conservation constant.

3. Results and discussion

Depok subbasin was modeled as one single lumped subbasin rather than divided into smaller subbasins. The calibration control point is located right at the location of the water level recorder station in Depok, 10 kilometers from South Jakarta. The limitations of this study is that the model assumes that all runoff flows into the river and ignores several river structures that might affect river flow such as Katulampa Water Gate and several dams. To get suitable soil moisture conditions, each simulation will be carried out in 3 days, starting from 2 days before the flood event and ending on the day of the flood. Flood discharge will be generated using a combination of 3 hydrograph units (Snyder, ITB, and SCS) and 2 rainfall intensity patterns (ABM and WJT [11]). Calibration was conducted on 3 rain events that caused flooding in Jakarta, especially along the Ciliwung River Basin, that has complete daily data on 9 rainfall stations used. Calibration and validation parameters used are lag time and initial abstraction (for SCS
UH), and lag time and peaking coefficient (for Snyder and ITB UH), each of which is initially determined by the United States Department of Agriculture (USDA) approach will be compared to the 3 values that give the smallest deviations. Figure 2 shows the calibration and validation processes of the 2015, 2016, and 2017 flood events. Table 3 shows the adjusted optimum lag time value for each method on different flood events.

![Figure 2](image)

**Figure 2.** Comparison between model simulation discharge with observation discharge, a) February 9th, 2015; b) April 21st, 2016; c) February 16th, 2017.

**Table 3.** Lag time parameter comparison for each scenario.

| Hydrograph Method | Flood Lag Time (Hour) |
|-------------------|-----------------------|
|                   | 2015  | 2016  | 2017  |
| Snyder UH - WJT   | 7.00  | 6.63  | 5.97  |
| SCS UH – WJT      | 5.50  | 5.32  | 5.28  |
| ITB UH – WJT      | 11.5  | 10.54 | 9.77  |
| Snyder UH – ABM   | 6.70  | 7.40  | 7.10  |
| SCS UH - ABM      | 6.33  | 6.73  | 6.40  |
| ITB UH - ABM      | 6.32  | 6.32  | 6 |

Note that on West Java trend rainfall, lag time values tend to decrease overtime, which is in accordance with CN lag time estimation. However, land cover changes are slightly different over the 1-
year period, not enough to show a visible impact. Theoretically, the difference between 2015 and 2017 lag time is 0.015 hours. To get better time lag change values, hourly rain record data must be used, and validation must be done with a wider time span. Table 4 shows that WJT rainfall distribution gives better NSE and RMSE than ABM, but the peak bias shows the opposite results. While the value of NSE and RMSE are the result of matching the pattern between observed flow and synthetic hydrograph, peak bias match between each peak of the observed flow and synthetic hydrograph. The RMSE, NSE, and peak bias error values will be averaged to get composite accuracy. The combination of West Java rainfall distribution and SCS UH with a lag time of 5.5 gives the smallest deviation, with composite accuracy of 83.3%, followed by ABM-SCS UH and WJT-Snyder UH with 82.5% and 82.4%, respectively. Theoretically, by dividing Depok subbasin into smaller subbasin the better result will be obtained. However, this can lead to bias of parameter values due to the unavailability of water level record in each subbasin.

### Table 4. Comparison of calibration and validation results.

| Rainfall Method        | Error | Unit Hydrograph |
|------------------------|-------|-----------------|
|                        |       | Snyder | SCS | ITB  |
| West Java Trend        | RMSE 1 | 0.567 | 0.600 | 0.600 |
|                        | RMSE 2 | 0.567 | 0.567 | 0.633 |
|                        | RMSE 3 | 0.600 | 0.567 | 0.800 |
|                        | NSE1   | 0.661 | 0.678 | 0.663 |
|                        | NSE2   | 0.639 | 0.661 | 0.572 |
|                        | NSE3   | 0.638 | 0.657 | 0.400 |
|                        | Bias1  | 1.08% | 1.04% | -12.08% |
|                        | Bias2  | 1.60% | 1.21% | -8.44% |
|                        | Bias3  | 1.84% | 1.26% | -5.44% |
| Alternating Block Method | RMSE 1 | 0.633 | 0.600 | 0.567 |
|                        | RMSE 2 | 0.633 | 0.567 | 0.567 |
|                        | RMSE 3 | 0.633 | 0.567 | 0.567 |
|                        | NSE1   | 0.579 | 0.640 | 0.654 |
|                        | NSE2   | 0.616 | 0.653 | 0.654 |
|                        | NSE3   | 0.611 | 0.644 | 0.659 |
|                        | Bias1  | 3.07% | 1.75% | -1.59% |
|                        | Bias2  | 0.83% | 0.22% | -1.59% |
|                        | Bias3  | -3.92% | -5.11% | -1.59% |

### 4. Conclusions

The present study is an attempt to estimate the fittest combination between rainfall distribution and unit hydrograph method towards the evolution of peak discharge and flood volume on Bogor subbasin, Indonesia. HEC-HMS was used to generate flood hydrographs to calibrate and validate flood discharges. The hydrological model was calibrated and validated using observed river discharge data on three flood events. The Snyder, ITB, and SCS Unit Hydrograph were compared in combination with two rainfall distribution approaches, i.e., the West Java Trend distribution and Alternating Block Method. Calibration and validation analysis show a combination of West Java rainfall distribution and SCS UH with a lag time of 5.5 gives the smallest deviation, with the accuracy of 83.3%, therefore it is recommended to be used to estimate the design flood hydrographs. Two other combinations that give good results are ABM-SCS UH and WJT-Snyder UH with 82.5% and 82.4% accuracies, respectively. The result of this study can further be used to improve the estimation of flooding due a combination of multiple causes, such as the effect of land cover change and land subsidence. Further development of this study might be conducted by using a semi-distributed or distributed model approach with hourly rainfall data input to improve calibration results.
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