The representative synthetic unit hydrograph in Juana watershed

AG Pradipta¹ and S Nurhady²
¹Department of Agricultural and Biosystems Engineering, Universitas Gadjah Mada, Indonesia
²CV Gama Tirtabumi, Indonesia

E-mail: ansita.pradipta@ugm.ac.id

Abstract. Rainfall-runoff transformation is carried out when the series of discharge data is limited or unavailable. One of the components of rainfall-runoff transformation is unit hydrograph, which can be derived synthetically. The selection of the representative synthetic unit hydrograph is fundamental related to the results of the further calculation. This study compared three types of synthetic unit hydrograph, that were Gama I, Nakayasu and SCS. The study was conducted in Juana Watershed, which is located in Central Java Province and composed of 52 sub-watersheds. The calculation was carried out in the control point of Sentul Weir by using HEC-HMS version 4.2.1, in the case of January 2014 flood events. The results showed that the peak discharge from Gama I, Nakayasu, and SCS synthetic unit hydrograph were 80.78 m³/s, 85.32 m³/s, and 78.89 m³/s respectively. Those results then compared with the flood mark in Sentul Weir, which was estimated 76.53 m³/s. Therefore, the SCS method was determined as the representative synthetic unit hydrograph in Juana Watershed, refers to the minimum error value of 3.08%. Then the analysis of design flood hydrograph for the 52 sub-watersheds in Juana Watershed can be approached by using the SCS synthetic unit hydrograph method.

1. Introduction
Juana Watershed, which has the catchment area of 1.283,9 km², is located in Central Java Province, Indonesia. It was almost every year, Juana Watershed and its tributaries overflow and caused material losses. Based on the data released by BPPD of Central Java Province, there were at least six flood events occurred in 2015. To manage and control the flood, then it is necessary to do hydrological analysis to determine the magnitude of the design flood discharge as a basis for planning flood control buildings.

Design flood hydrograph analysis can be carried out according to data availability. In general, the discharge record is often not available well enough. It means there is no discharge record in the river to be analyzed, the location of the discharge record does not fit to the analysis control point, the discharge data is not long enough to be analyzed, and the data only record the peak discharge. Besides that, usually, there are no data pairs of discharge and rainfall records at the same time with short intervals (e.g., hourly interval). To overcome those problems, a design flood hydrograph analysis can be carried out using rainfall-runoff transformation method, which involves the components of unit hydrograph, excess rainfall, and baseflow.

Regarding the flood model history, unit hydrograph known as the important characteristics in the watershed [1]. There are two methods of unit hydrograph analysis, which are measured unit hydrograph
and synthetic unit hydrograph. The measured unit hydrograph analysis requires the data pairs of discharge and rainfall records at the same time with short intervals. Those data are not available in Juana Watershed. Therefore, the component of unit hydrograph can be approached by synthetic unit hydrograph.

The term synthetic means that the unit hydrograph derived from watershed characteristics, rather than rainfall-runoff data records. The method of synthetic unit hydrograph analysis consists of several types, each type using different parameters, and showing the different performance in each watershed. Ideally, every watershed has its particular unit hydrograph. To determine the representative unit hydrograph in Juana Watershed, the calculation results need to be verified with field conditions.

The basic idea of this research is to compare the peak discharge from the calculation of three methods of synthetic unit hydrographs with the maximum flood trace that overflows above a transverse threshold of the river. Those methods are Gama I-UH, Nakayasu UH, and SCS-UH. Synthetic unit hydrograph procedures are used to develop unit hydrographs for other locations on stream in the same watersheds or nearby watersheds of a similar character.

2. Methodology

The flood hydrograph analysis utilizes the rainfall-runoff transformation method, which involves several components such as, unit hydrograph, excess rainfall, and baseflow. Unit hydrograph concept was first proposed by Sherman (1932) and has developed become one of the most powerful tools in applied hydrology. The Unit Hydrograph (UH) of a watershed is defined as the direct runoff hydrograph resulting from a unit volume of excess rainfall of constant intensity and uniformly distributed over the drainage area. There are two types of UH, which are measured and synthetic UH. The methods of synthetic unit hydrograph used in this study are Gama I-UH, Nakayasu UH, and SCS-UH.

2.1. Gama I-UH

Gama I-UH consists of four main variables as below.

Time to rise,

\[ TR = 0.43 \left( \frac{L}{100SF} \right)^3 + 1.0665SIM + 1.2775 \]  (1)

Peak discharge,

\[ Q_p = 0.1836A^{0.5886}TR^{-0.4008}JN^{0.2381} \]  (2)

Time to base,

\[ TB = 27.4132TR^{0.1457}S^{-0.0986}SN^{0.7344}RU^{0.2574}A^{0.574} \]  (3)

Recession limb, which is determined by a storage coefficient,

\[ K = 0.5617A^{0.1798}S^{-0.1446}SF^{-1.0897}P^{-0.0452} \]  (4)

with the amount of discharge in recession limb is,

\[ Q_t = QP_{t}^{-t/K} \]  (5)

The input parameters of Gama I-UH are:
- Source factor \((SF)\) that is the comparison of the total length of level 1’s rivers with the total length of rivers in all levels.
- Source frequency \((SN)\) that is the comparison of the total number of level 1’s rivers with the total number of rivers in all levels.
- Symmetry factor \((SIM)\) that is the multiplication result of the width factor \((WF)\) and the relative upstream area of the watershed \((RUA)\).
- Width factor (WF) that is the comparison of the watershed width measured from the distance of 0.75 $L$ and 0.25 $L$ from the watershed control point.
- Relative upstream area (RUA) is the comparison of the upstream area of the watershed which is limited by a line drawn through a point on the river closest to the watershed centroid, and perpendicular to the line connecting the point to the measurement point, with the total watershed area ($A$).
- Joint number (JN) the amount is equal to the total number of level 1’s rivers minus one.
- Drainage network density ($D$) that is the total length of rivers divided by watershed area.

2.2. Nakayasu UH

Nakayasu UH can be determined by using the following equations [10].

$$Q_P = \frac{A}{3.6} \left( \frac{R_e}{0.3T_P + T_{0.3}} \right)$$

(6)

$$T_P = t_g + 0.8T_r$$

(7)

$$t_g = 0.4 + 0.058L \quad \text{for } L > 15 \text{ km}$$

(8)

$$t_g = 0.21L^{0.7} \quad \text{for } L < 15 \text{ km}$$

(9)

$$T_{0.3} = \alpha t_g$$

(10)

where:
- $Q_P$ = flood peak discharge ($m^3/s$)
- $A$ = watershed area ($km^2$)
- $R_e$ = effective rainfall (1 mm)
- $T_P$ = time to peak (hour)
- $T_{0.3}$ = time from the peak discharge until 0.3 times of peak discharge (hour)
- $t_g$ = time of concentration (hour)
- $T_r$ = time of rainfall (hour)
- $\alpha$ = watershed characteristic coefficient
- $L$ = length of the main river (m)

The shape of the unit hydrograph is given by the following equations.

**Rising limb ($0 < t < T_P$)**

$$Q_t = Q_P \left( \frac{t}{T_P} \right)^{2.4}$$

(11)

**Recession limb ($T_P < t < T_P + T_{0.3}$)**

$$Q_r = Q_P \times 0.3 \left( \frac{t - T_P}{T_{0.3}} \right)$$

(12)

**Recession limb ($T_P + T_{0.3} < t < T_P + T_{0.3} + 1.5T_{0.3}$)**

$$Q_t = Q_P \times 0.3 \left( \frac{t - T_P}{0.5T_{0.3}} \right) \left( \frac{1.5T_{0.3}}{T_{0.3}} \right)$$

(13)

**Recession limb ($t > T_P + T_{0.3} + 1.5T_{0.3}$)**

$$Q_t = Q_P \times 0.3 \left( \frac{t - T_P}{1.5T_{0.3}} \right) \left( \frac{1}{2T_{0.3}} \right)$$

(14)
2.3. SCS UH

This method uses the dimensionless hydrograph, which is developed from the majority of unit hydrograph analysis from the several watershed data and locations [10]. The used equations as below [11]

\[ Q_p = \frac{0.208A}{p_r} \]  
\[ p_r = \frac{t_c}{z} + t_p \]

where:
- \( Q_p \) = peak discharge (m³/s)
- \( A \) = watershed area (km²)
- \( t_r \) = duration of effective rainfall (hour)
- \( t_p \) = the difference between the center duration of effective rainfall and the UH peak (hour)

\( tp \) can be defined as \( 0.6 \times t_c \), and \( t_c \) is a time of concentration which can be determined using the Kirpich equation as below [11].

\[ t_c = 0.0663L^{0.77}S^{-0.385} \]

where:
- \( t_c \) = time of concentration (hour)
- \( L \) = the length of the main river (km)
- \( S \) = the slope of the main river

2.4. Excess Rainfall

Rainfall is the most important input component in hydrology process because it will be transformed to be the flow in the river, through the surface runoff, interflow, subsurface flow, or groundwater flow. Therefore, the measurement of rainfall must be done as carefully as possible [9].

The excess rainfall is the rainfall, which causes direct runoff. The magnitude of excess rainfall can be approached by subtracting the precipitation with the losses. There are several methods to calculate the losses; one of them is the Soil Conservation Service Curve Number method given in the following equations [12]. Curve Number (CN) is based on soils, plant cover, amount of impervious areas, interception, and surface storage. The United States Department of Agriculture (USDA) gives several CN that can be used as the reference [12].

\[ S = \left( \frac{1000}{CN-10} \right) \times 25.4 \]  
\[ I_a = 0.2S \]  
\[ P_e = \frac{(P-I_a)^2}{P-I_a+S} \]

where:
- \( CN \) = curve number
- \( S \) = maximum potential retention
- \( I_a \) = initial abstraction
- \( P_e \) = total excess rainfall on \( t \)
- \( P \) = total precipitation on \( t \)

2.5. Baseflow

As the Unit Hydrograph concept applies only to direct runoff, the direct runoff must be separated from the baseflow [8]. The amount of baseflow is obtained using the equation given by Gama I-UH as below [9].
\[ Q_B = 0.4715A^{0.6444}D^{0.9440} \]  \hspace{1cm} (21)

where:
- \( Q_B \) = baseflow (m\(^3\)/s)
- \( A \) = watershed area (km\(^2\))
- \( D \) = drainage network density (km/km\(^2\))

2.6. The search for flood trace
Juana Watershed has two automatic water level recorder (AWLR) station, located in Bulung Cangkring and Tanjang Bridge. Recently, those two AWLR station is not well functioned. Besides that, the historical data were not available in the related authorities. Therefore, to verify the results of the calculation, a flood trace observation was carried out on the transverse threshold structure of the river.

There are two potential locations to verify the calculation results, that are in the Logung Weir and Sentul Weir. Based on information from related authorities, Juana Watershed suffered heavy flood events in January 2014. During this period, there was a construction activity in the upstream of Logung Weir. The construction has resulted in the reduction of the peak flood discharge which overflows over the Logung Weir so that the flood trace in Logung Weir cannot be used as material for verification of calculations. Thus, verification of the calculation results can only be done at the Sentul Weir location.

Based on the results of the search for flood trace and information from the society, it can be obtained the flood water level above the dam crest \((H)\) and the measured dam width \((B)\). The discharge through the dam crest can be calculated using the following equation [13].

\[ Q = C_d \times B \times H^{3/2} \]  \hspace{1cm} (22)

where:
- \( Q \) = discharge through the dam crest (m\(^3\)/s)
- \( C_d \) = discharge coefficient
- \( B \) = width of dam crest (m)
- \( H \) = water level above the dam crest (m)

![Figure 1. Schematic of Juana Watershed.](image-url)
3. Results and Discussion

Flood hydrograph analysis uses the rainfall-runoff transformation method, which involves several components. Those components include excess rainfall, unit hydrograph, and baseflow. Each of those components is described in the points below.

3.1. Excess Rainfall

There are 11 rainfall stations in the Juana watershed, but none are included in the Sentul Weir catchment area (it can be seen in Figure 1). Therefore, the analysis of regional rainfall uses data from other nearby stations outside the Sentul Weir catchment area, namely the 191 Cabean/Kedunglo rainfall station. Based on the recording of rainfall data, the largest rainfall in January 2014 occurred on the 23rd, which was equal to 90 mm. The rainfall is then distributed to within a few hours. Analysis of the distribution of hourly rainfall was carried out using the rainfall distribution pattern at the Mijen Station, where is the closest location of automatic rainfall recorder (ARR). According to [14], rainfall at Mijen Station was distributed to 6 hours, with the hourly distribution patterns were 9.28%, 23.82%, 22.56%, 18.40%, 11.00%, and 14.94%. Based on this distribution, 90 mm rainfall in the Sentul Weir catchment area can be distributed as shown in Figure 3.

![Figure 2. The Search for Flood Trace in Sentul Weir.](image)

![Figure 3. Distribution of Hourly Rainfall in Sentul Weir Catchment Area.](image)
3.2. Losses

The amount of losses affects excess rainfall, which will produce direct runoff. The method used in calculating losses in this study is the SCS-CN method. United States Department of Agriculture (USDA) has released the CN table that contains various type of land use, described on the technical release 55. Based on the soil type map, most of the soil in the Juana watershed are included in group B. Furthermore, by using the land use map and the CN table, it can be obtained the amount of average CN for Sentul Weir Catchment Area as shown in Table 1. With the CN value of 76.94, it can be obtained that the $I_a$ value was 15.22 mm.

**Table 1. Calculation of Average CN in Sentul Weir Catchment Area**

| Type of Landuse | Area (km$^2$) | Curve Number | $CN \times A$ |
|-----------------|---------------|--------------|---------------|
| Paddy field     | 20.70         | 76.00        | 1573.2        |
| Grass           | 7.35          | 69.00        | 507.15        |
| Residential     | 4.35          | 85.00        | 369.75        |
| Cultivation     | 15.54         | 81.00        | 1258.74       |
| Forest          | 1.19          | 60.00        | 71.4          |
| **Total**       | **49.13**     | **3780.24**  |               |
| **Average**     |               | **76.94**    |               |

3.3. Unit Hydrograph

There are three methods of synthetic unit hydrographs used in this study, namely Gama I-UH, Nakayasu UH, and SCS UH. The results of the calculation of Gama I-UH in Sentul Weir Catchment Area can be seen in Table 2, while the results of Nakayasu UH calculations can be seen in Table 3. Graphs of Gama I-UH and Nakayasu UH can be seen in Figure 4. For SCS-UH, unit hydrograph calculations are carried out automatically using the HEC-HMS Software version 4.2.1, which can directly produce a flood hydrograph. The inputs for the SCS-UH method in the HEC-HMS software were the catchment area ($A$) of 49.13 km$^2$, $tc$ of 8.25 hours, and $t_{ag}$ of 297 minutes $(0.6 \times tc)$.

**Table 2. Results of Calculation of Gama I-UH in Sentul Weir Catchment Area**

| No. | Parameter | Symbol | Unit | Value |
|-----|-----------|--------|------|-------|
| 1.  | Total length of level 1’s rivers | $L_1$ | km   | 69.40 |
| 2.  | Total length of rivers in all levels | $L$ | km   | 138.90 |
| 3.  | Number of level 1’s rivers | $N$ | pcs | 118.00 |
| 4.  | Number of rivers in all levels | $N'$ | pcs | 234.00 |
| 5.  | Upper width of catchment area | $W_L$ | km | 4.05 |
| 6.  | Lower width of catchment area | $W_U$ | km | 3.08 |
| 7.  | Upstream elevation of the river | $E_u$ | m | 250.00 |
| 8.  | Downstream elevation of the river | $E_d$ | m | 24.00 |
| 9.  | Catchment area | $A$ | km$^2$ | 49.13 |
| 10. | Upstream area of the river | $A_U$ | km$^2$ | 28.08 |
| 11. | Length of the main river | $L$ | km | 26.80 |

**Calculation Results**

| No. | Parameter | Symbol | Unit | Value |
|-----|-----------|--------|------|-------|
| 1.  | Source factor | $SF$ | - | 0.50 |
| 2.  | Width factor | $WF$ | - | 1.32 |
| 3.  | Relative upstream area of the watershed | $RU/A$ | - | 0.57 |
| 4.  | Symmetry factor | $SIM$ | - | 0.75 |
| 5.  | Joint number of the river | $JN$ | - | 117.00 |
| 6.  | The average slope of the river | $S$ | - | 0.01 |
| 7.  | Source frequency | $SN$ | - | 0.50 |
| 8.  | Drainage network density | $D$ | km/km$^2$ | 2.83 |
| 9.  | Time to rise | $TR$ | hour | 2.15 |
| 10. | Peak discharge | $Q_p$ | m$^3$/s | 8.16 |
| 11. | Time to base | $T_b$ | hour | 25.70 |
| 12. | Storage coefficient | $K$ | hour | 5.04 |
| 13. | Basafloss | $Q_b$ | m$^3$/s | 15.57 |
Table 3. Results of Calculation of Nakayasu UH in Sentul Weir Catchment Area

| No. | Parameter                              | Symbol | Unit  | Value |
|-----|----------------------------------------|--------|-------|-------|
|     | Data                                   |        |       |       |
| 1   | Catchment area                         | $A$    | km$^2$| 49.13 |
| 2   | Length of the main river               | $L$    | km    | 26.80 |
| 3   | Coefficient of watershed characteristic| $\alpha$|       | 2.00  |
|     | Calculation Results                    |        |       |       |
| 1   | Time to rise ($1.4 - 2 t_g$)           | $T_p$  | hour  | 3.32  |
| 2   | Time from the peak until $0.3 \times Q_p$| $T_{0.3}$| hour  | 3.91  |
| 3   | Time of concentration                  | $t_g$  | hour  | 1.95  |
| 4   | Peak discharge                         | $Q_p$  | m$^3$/s| 2.78  |
| 5   | Recession limb                         |        |       |       |
|     | $- T_p + T_{0.3}$                      | hour   | 7.23  |
|     | $- T_p + T_{0.3} + 1.5T_{0.3}$         | hour   | 13.09 |

Figure 4. Gama I and Nakayasu UH.

3.4. Baseflow

The amount of baseflow is obtained by using the equation given by the Gama I-UH method (equation 22). The input parameter of baseflow calculation is catchment area and drainage network density (it can be seen in Table 2). The catchment area is 49.13 km$^2$, and the drainage network density is 2.83 km/km$^2$, then the baseflow is obtained at 15.57 m$^3$/s.

3.5. Water level data (discharge)

Based on the search for flood trace (Figure 2), the highest water level during the January 2014 flood reached 140 cm above the dam crest. The length of the dam crest is measured using a rolling meter, and the length is 22 m (Figure 2). Then the discharge through the dam crest can be calculated using equation 23 so that the amount of discharge is 76.53 m$^3$/s.
3.6. Results of model verification

From the analysis results of the distribution of hourly rain, losses, three method unit hydrographs, and baseflow analysis, it was then entered into the HEC-HMS Software version 4.2.1 for the flood hydrograph simulation (Figure 5). Based on Figure 5, it can be seen that the peak flood discharge with Gama I-UH method, Nakayasu UH, and SCS-UH are 80.78 m$^3$/s, 85.32 m$^3$/s, and 78.89 m$^3$/s respectively. The peak flood discharge was then compared to the actual flood discharge in January 2014, which was 76.53 m$^3$/s. It can be seen that the closest result is the SCS-UH method with an error value of 3.08%. It means that the SCS-UH is the representative synthetic unit hydrograph in Juana Watershed. Therefore, for the analysis of design flood hydrograph in 52 sub-watersheds in the Juana watershed can be approached using the SCS-UH method.

### Table 4. Results of Calculation of Nakayas UH in Sentul Weir Catchment Area

| Method       | Estimated Peak flood discharge, $Q_p$ (m$^3$/s) | Error value (%) |
|--------------|-----------------------------------------------|-----------------|
| Gama I-UH    | 80.78                                         | 5.55            |
| Nakayasu UH  | 85.32                                         | 11.49           |
| SCS-UH       | 78.89                                         | 3.08            |

![Figure 5. Comparison of the Flood Hydrograph From The Three Synthetic Unit Hydrograph Methods.](image)

4. Conclusion

A hydrological analysis is required in the planning of flood management and control in Juana Watershed. A unit hydrograph is one of the components used in the hydrological analysis. In this study, there are three methods of synthetic unit hydrograph, whose flood discharge are verified with the actual flood discharge in January 2014. The reference point in the verification is Sentul Weir, with a flood discharge of 76.53 m$^3$/s. From the analysis results, the peak flood discharge obtained with the Gama I-UH method, Nakayasu UH, and SCS UH were 80.78 m$^3$/s, 85.32 m$^3$/s, and 78.89 m$^3$/s respectively. The peak flood discharge with the SCS-UH method is closest to the actual flood discharge value in Sentul Weir, with an error value of 3.08%. Therefore, SCS-UH is the representative synthetic unit hydrograph in Juana watershed and can be used as the method in flood hydrograph analysis in 52 sub-watersheds in Juana watershed.
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