Unit hydrograph method for curve number validation in hydrological modeling: case study of Welaran Watershed, Karangsambung, Kebumen

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Abstract. Unit hydrographs, which have long been used in hydrological analyses, assume or require evenly distributed rainfall as their input. In practice, such a requirement is met when the methods are applied to small watersheds. This study aim to validate the curve number in hydrological modelling used unit hydrograph. The Welaran Watershed in Karangsambung has an area of 11.6 km². More than 50% of it is covered by rice fields, while the rest is by dry agricultural lands, multiple-species plantations, and settlements. This watershed has been installed with a stream gauge equipped with AWLR and ARR. Based on the automatically recorded flood and rainfall data, a hydrological analysis was performed to generate unit hydrographs. Baseflow (losses), separated from the hydrograph, was compared with a loss of water using the Curve Number (CN) method. CN was derived from a reference table containing land use (LU), soil hydrological group, and antecedent moisture condition (AMC). The CN of the study area was 67, which is the weighted value of the mapping unit. In some rainfall-runoff events, the unit hydrograph approach yielded curve numbers varying between 23-82 for eight selected rainfall events. It indicates that many factors shape the diversification of rainfall-runoff interaction in a watershed, including the actual distribution of rain. Also, AMC seemed to be distributed according to not only the amount of previous rain but also other factors that need further study.

1. Introduction
A watershed is an area that is topographically bordered by ridges from which water moves downhill towards one stream [5]. In watersheds, surface runoff is formed through a complicated process. It is part of the rainfall that flows over the land surface toward rivers, lakes, and oceans. It develops when the amount of rain exceeds soil infiltration [1]. There are three things contributing to high surface runoff, namely (1) human interventions that have converted land use and induced changes on nature, (2) meteorological events, such as extreme rains and cyclones, and (3) land degradation, such as river siltation due to sedimentation, loss of vegetation that covers the soil, and the narrowing of river channel. High surface runoff and loss of soil from agricultural land are widespread and pose a significant threat to agricultural and environmental productivity in many developing regions in the world [6].
A water level or stage hydrograph records surface runoff in a watershed. Then, based on the rating curve (RC) equation, it is converted to a discharge hydrograph. The essential role of RC requires a separate study, particularly that of accuracy in discharge measurement, from which the shape of hydrograph of a watershed can be identified. During the rainfall-runoff process, a watershed produces a hydrograph whose aspects depend on several factors, including its physical features (e.g., vegetation cover, topography, soil properties, river systems, and flow patterns), rainfall characteristics, and the existence of hydrological structures. Flow hydrographs always change following the attributes of a watershed and the amount and time of the input. HEC-HMS (Hydrologic Engineering Center-Hydrologic Modelling Systems) is one of the models developed for hydrological analyses that simulate the rainfall-runoff processes. The output is a unit hydrograph that can be used directly or combined with other computer programs for water availability, urban drainage, forecasting of urbanization impact, overflow design, flood damage reduction, flood management regulations, and hydrological operation systems [10].

Welaran is a sub-watershed of Lukulo in Karangsambung District, Kebumen Regency, Central Java. It covers an area of 11.6 km², with slopes varying from flat to very steep depending on geological conditions and erosion and denudation processes. The dominant flow patterns are sub-parallel, semi-trellis, and dendritic, suggesting that geological structures considerably control the area. Welaran Watershed has a distinctive characteristic, that is, bowl-like shape, which allows water from all surfaces to flow towards one stream. This rounded shape causes the rainfall accumulating in the channel to transform into runoff and drain rapidly. Hilly topography and round shape with a circularity ratio of 0.65 are the factors contributing to the formation of large runoff in a short time.

Welaran Watershed that belongs to the Karangsambung geological reserve has many rock outcrops that are not covered by vegetation [8]. For this reason, most portion of precipitation transforms into surface runoff. The land in this watershed is mostly used for rice fields, meaning that its hydrological response is controlled by cultivated land and terracing system. The soil texture in this agricultural land is clay, which is impermeable and has a high coefficient of runoff. However, the terrace systems can retain water temporarily in plots of rice fields and, consequently, reduce the rate of runoff. This paper analyzes the characteristics of rainfall-runoff relationship in Welaran Watershed from flow hydrographs and calculates runoff using the SCS-CN method.

2. Methods
This study used primary and secondary data. The primary data collected in the field were rainfall and water level. Meanwhile, the secondary data, which were obtained from several related agencies, included monthly rainfall, satellite imagery, soil maps, the 1:25,000 topographic maps, and geological maps. The survey equipment consisted of AWLR (Automatic Water Level Recorder) and ARR (Automatic Rainfall Recorder) loggers, measuring tapes, Global Positioning System (GPS), digital cameras, and checklists. For data analysis, this study also used a set of computers installed with ArcGIS 10.3, HEC-GeoHMS 10.3, HEC-HMS 4.0, and Microsoft Office 2007.

Flow coefficient illustrates runoff that represents the effects of the watershed on precipitation loss into surface runoff. The morphometry of the watershed was processed using the HEC-GeoHMS extension with a terrain preprocessing arrangement. In the field, the discharge was measured using the slope area method. Another set of discharge data were calculated with the calibration curve method based on the discharge measured at various water levels. The method used to calculate the runoff coefficients was the curve number (CN), known as the Soil Conservation Service-Curve Number (SCS-CN) [10]. As for the hydrograph modeling, the study used the HEC-HMS software and analyzed two data, namely measured hydrograph and modeled hydrograph. The rainfall-runoff model performed in HEC-HMS computed precipitation, runoff volume, direct runoff, and baseflow.

2.1. Calculating the modeled runoff volume using SCS-Curve Number
The SCS-CN method estimates that rainfall that produces runoff is a function of cumulative rainfall, land use, soil type, and antecedent soil moisture. The SCS calculation is shown in equation (1).

\[ Pe = \frac{(P-Ia)^2}{P-Ia+S} \]  

Where \( Pe \) is the accumulation of effective rain at time \( t \), \( P \) is the accumulation of rain depth at time \( t \), \( Ia \) is an initial loss, and \( S \) is maximum storage capacity. Based on the results of many experiments in small watersheds, SCS has developed an empirical relationship between \( Ia \) and \( S \) in equation (2).

\[ Ia = 0.2 \times S \]  

The accumulation of effective rain at time \( t \) is presented in equation (3).

\[ Pe = \frac{(P-0.2S)^2}{P+0.8S} \]  

The relationship between the characteristics of a watershed and maximum storage capacity is presented in Curve Number (CN), as showed in equation (4).

\[ S = \frac{25400-254 \times CN}{CN} \text{ (mm)} \]  

CN ranges from 100 (impervious layer) to around 20 for highly permeable soils (i.e., high infiltration rate). For a watershed consisting of several types of soil and land use, the composite curve number (CN composite) is calculated with equation (5).

\[ CN_{\text{composite}} = \frac{\sum AiCN_i}{\sum Ai} \]  

where \( CN_{\text{composite}} \) is the composite curve number used in the calculation of runoff volume, \( i \) is the index of the watershed mapping unit that is composed of uniform land use and soil types, \( CNi \) is the curve number of the mapping unit \( i \), and \( Ai \) is the area of the mapping unit \( i \).

Based on selected hydrographs from several rain events, an analysis was performed to generate a unit hydrograph (UH). The separation of baseflow from the flood hydrograph was carried out by a conventional graphical method. Afterward, the direct runoff (DRO) was separated and used in the calculation of DRO volume. The DRO volume is the same as the effective rain that falls within the watershed area. Losses of water can occur due to various factors, such as infiltration capacity and surface storage. The ordinate of the unit hydrograph can be derived from that of DRO and effective rain. Afterward, several unit hydrographs were analyzed and calculated to produce mean values. Then, the mean value (master unit hydrograph) can be used to assess the flood hydrographs based on rainfall data in the study area.

The effective rain that had been calculated from each unit hydrograph analysis was analyzed and compared with the SCS-CN method. The CN was determined by trial and error to yield runoff volume that matched the DRO volume.

3. Results and Discussion

Welaran Watershed, based on the Universal Transverse Mercator (UTM) coordinate system, is located between 354025-358549 mE and 9162260-9166467 mN. It administratively lies in Karangsambung District in Kebumen Regency, Central Java Province, and covers four villages, namely Banioro, Langse, Kalisana, and Tlepok. It has an area of 11.616 km² and is a sub-watershed of Lukulo. Moreover, it has three major morphological units, namely mountains, hills, and plains. Nearly flat topography dominates 30.7% of the watershed area, followed by slightly sloping (25.9%), sloping
(23.6%), slightly steep (11.2%), flat (8.4%), and steep (0.7%). Brown and red latosols prevail the peak to the upper slope of the watershed, while red-yellow podzolic is mainly found in the middle to the lower slopes [8]. The watershed receives daily precipitation from 19 to 585 mm, with an annual average of 3,716 mm. According to the Oldeman classification, the climate of this region is C2 with 4-5 consecutive wet months per year and 2-3 consecutive dry months per year. Accordingly, rice fields can only grow in one long season and a crop rotation system with CGPRT (coarse grains, pulses, roots and tuber) in dry seasons.

Rain as an input can demonstrate the hydrological process in a watershed straightforwardly [3]. The rainfall in Welaran Watershed was observed from November 2018 to March 2019. Daily rainfall data were collected from an automatic tipping-bucket rain gauge station (see Figure 2). These data were used to calculate surface runoff with the SCS-CN method.

The amount, distribution, and intensity of rainfall affect the quantity and variation of river discharge [9]. The highest rainfall occurred on January 16, 2019, with a depth of 72.2 mm. The peak of the rainy season from November to March was in January, with a depth of 397.6 mm. The regional rainfall tended to have a short duration with high intensity. According to the Meteorology, Climatology, and Geophysics Agency (BMKG), rainfall with an intensity of 10-100 mm/day like the Welaran Watershed is categorized as heavy to very heavy. Rainfall produces a different amount of discharge in the time dimension. Most portion of the first rainfall after dry seasons is absorbed into the ground. After several rain events, and the soil has reached saturation point, rainwater likely transforms into surface flows.

![Image](image.png)

**Figure 1.** The land use map of Welaran Watershed based on several sources and ground check in 2019.
Figure 2. The daily rainfall of Welaran Watershed in November 2018-March 2019

The discharge was gauged 22 times from November to April. The highest discharge was recorded on December 4, 2018 (34.79 m$^3$/s), whereas the lowest one was on November 17, 2018 (6.23 m$^3$/s). The lowest discharge occurred at the beginning of the rainy season in which rain was not intensive yet. The rating curve is illustrated by a graph correlating water level (stage) with measured discharge in the field. The stage-discharge relationship had the $R^2$ value of 0.99, and the closer it is to 1, the stronger the positive correlation is. With the best-fit method, this relationship produced equation (6) and Figure 3.

$$Q = 14.98 \times H^{0.772}$$

(6)

Figure 3. The rating curve of Welaran River in 2018-2019

The river flow discharge varied from 6.23 m$^3$/s to, the highest, 34.79 m$^3$/s. Then, these data were paired with their corresponding rainfall to identify their relationship. The rain-discharge interaction in Welaran Watershed is illustrated in Figure 4.
Figure 4. The flow hydrograph and rainfall in Welaran Watershed from November 18, 2018, to January 31, 2019

Many factors determine the form of a hydrograph. Among others, the shape of a watershed affects the time of water flow and other elements of the hydrograph itself [4]. The flood hydrograph in Welaran Watershed has a tapered form or a steep increasing and decreasing limbs (Figure 5), which imply that the river discharge peaks and returns to its original level rapidly. Six floods and eight rainfall events were selected to analyze each period and characteristic of the flow hydrograph. The lapse of time between rainfall and flood and between flood peak and its complete recession varies by rain duration and intensity. High rainfall intensity leads to rapid peak time, as apparent from the nearly vertical rising limb.

Table 1 summarizes several hydrological parameters for the selected rains in Welaran Watershed. The six chosen events are hydrographs with effective rain, that is, a depth of rainfall assumed to have been evenly distributed throughout the watershed. As derived from baseflow separation, the unit hydrographs are depicted in Figure 6 (a-f). These hydrographs show a total runoff discharge of averagely 9654.3 m$^3$/s, baseflow discharge of 6,217.72 m$^3$, direct runoff of 3,436.58 m$^3$/s, and effective rain of 1,065.1 mm. These figures are the mean values of several events that have different characteristics in each period. The hydrograph separation and the SCS-CN calculation yielded different effective rains with an RMSE value of 0.95.

Table 1. Summary of the hydrological parameters of selected rainfall-runoff events in Welaran Watershed

|                  | Nov 29 | Dec 4 | Dec 7 | Dec 10 | Dec 24 | Jan 3 | Jan 16 | Jan 23 |
|------------------|--------|-------|-------|--------|--------|-------|--------|--------|
| Cumulative rain (mm) | 28.8   | 46.8  | 22.8  | 14.8   | 17.4   | 15.8  | 25.4   |
| Rain duration (minute) | 150    | 250   | 130   | 330    | 160    | 150   | 150    |
| Effective rain - Pe (%) | 17.8   | 0.9   | 18.6  | 0.8    | 12.2   | 80.6  | 14.8   |
| Effective rain - Pe (mm) | 5.13   | 0.41  | 4.24  | 0.12   | 2.13   | 12.73 | 3.76   |
| Peak discharge of UH (m$^3$/det) | 59,638 | 4,769 | 49,290| 1,377  | 24,703 | 147,862 | 43,731 |
| Volume of DRO (m$^3$) |        |       |       |        |        |       |        |
Figure 5. The selected flood hydrographs in Welaran Watershed

Figure 6. The unit hydrographs for eight selected rain events in Welaran Watershed
3.1. Curve Numbers by the SCS-CN Method

Based on the soil type, the soil hydrological groups in the Welaran Watershed have been divided into two, namely group A and group C. The soils in question are latosol and podzolic. Latosol is clay-textured and located on the upper slope, from which this soil is categorized as soil hydrological group A. According to [9], group A consists of soils with low runoff potential and high infiltration rate. As for podzolic, it spreads from the middle to the lower slope of the watershed and is categorized as soil hydrological group C. Group C consists of soils with a rather high runoff potential and slow infiltration rate if the soil is completely wet.

Land use and land cover conditions affect the process of rainwater turning into surface runoff. Vegetation cover and land treatment modify the infiltration process aside from the static factor, that is, soil type. This study differentiates five land uses in Welaran Watershed, namely rice fields, settlements, multiple-species plantations, dry agricultural farms, and body of water. Rice fields are the dominant land use in the Welaran Watershed. Agricultural fields can be classified according to land treatment and the used sources of water. Land treatment controls water flow, and in the study area, it involves contour plowing and terrace farming. The source of water used for the agricultural practices in the watershed is rainwater.

Rain-fed rice fields use water from rain and, for this reason, significantly depend on the meteorological season. They generally do not have permanent irrigation structures and are infertile and susceptible to drought [7]. Due to poor hydrological treatment, they have a higher rate of runoff compared with that of irrigated rice fields. However, there are particular treatments to reduce it, namely constructing terraces and mounds on each topographic change. These modifications, termed mechanical conservation, aim to decelerate the rate of surface flow on rice fields. Otherwise, a fast runoff can wash away fertilizers and nutrients in the soil and, by extension, diminish agricultural productivity [2]. Rice is cultivated in rainy seasons, while tobacco and corn are grown in dry seasons. Rice is planted one or two times before the onset of the rainy season until the start of the dry season.
The other land use in Welaran Watershed includes multiple-species plantations and dry agricultural lands. Dry agricultural lands are planted with annual crops and located separately from the cultivated yards surrounding the local houses, also their use is stationary. Multiple-species plantations are lands grown with more than one species of crops that produce flowers, fruits, and saps, and their products are not harvested by tree logging. The settlements are mainly associated with rivers and roads, creating linear and clustered patterns. The water bodies in the watershed comprise the main channel of Welaran River and its tributaries. The source of this river is springs that mostly emerge on the breaks of slopes.

The curve number in the SCS-CN method is calculated based on soil hydrology group, land use, and antecedent moisture condition. Higher CN decreases the maximum storage capacity of the soil and precipitation loss but increases the accumulation of effective rain. Based on Table 2, the highest CN is in water bodies or impervious areas, whereas the lowest one is in dry agricultural lands. Compared with the soil hydrological group C, group A has a smaller CN. It is attributable to soil type and infiltration characteristics.

Based on the model generated by the HEC-GeoHMS method, the curve number varies between 30 to 100. The composite curve numbers were 67 in the CN II category or normal condition and 82.4 in the CN III category or wet condition. From the upper to part of the middle slopes of Welaran Watershed, the CN was low. Meanwhile, the middle to the lower slope had high CN.

Table 2. The curve number calculation of Welaran Watershed

| Land Use                        | Soil Hydrological Groups | Curve Numbers (CN) | Areas (A; km²) | A*CN   |
|---------------------------------|--------------------------|--------------------|----------------|--------|
| Settlements                    | A                        | 57                 | 0.07443        | 4.2424 |
|                                 | C                        | 81                 | 0.70905        | 57.4326|
| Rice Fields                     | A                        | 65                 | 1.03905        | 67.538 |
|                                 | C                        | 82                 | 4.17218        | 342.119|
| Dry Agricultural Lands          | A                        | 30                 | 2.08062        | 62.4185|
|                                 | C                        | 70                 | 2.21508        | 155.056|
| Multiple-species Plantations    | A                        | 45                 | 0.43097        | 19.3937|
|                                 | C                        | 77                 | 0.82263        | 63.3424|
Table 3. The Curve Number (CN) estimation based on DRO derived from the unit hydrographs of selected rain events in Welaran Watershed

| No | Codes | Dates   | Daily rainfall (mm) | Previous rainfall (mm) | The thickness of DRO from UH (mm) | Estimated CN |
|----|-------|---------|---------------------|------------------------|---------------------------------|--------------|
| 1  | A     | Nov 29  | 50,8                | 69                     | 0                               | 5,13         |
| 2  | C     | Dec 4   | 47,4                | 56,6                   | 50,2                            | 0,41         |
| 3  | D     | Dec 7   | 28,8                | 126,2                  | 11,8                            | 4,24         |
| 4  | E     | Dec 10  | 26                  | 57,4                   | 0                               | 1,10         |
| 5  | F     | Dec 24  | 20,2                | 4,6                    | 0                               | 0,12         |
| 6  | G     | Jan 3   | 24,2                | 39,4                   | 22                              | 2,13         |
| 7  | H     | Jan 16  | 72,2                | 50,4                   | 0                               | 12,73        |
| 8  | I     | Jan 23  | 31,6                | 66                     | 19,4                            | 3,76         |

3.2. Analysis of Hydrograph Model with HEC-HMS

Hydrograph analysis using HEC-HMS requires the initial condition of a watershed as an input to the predefined models. HEC-HMS consists of SCS-CN modeling to calculate loss, SCS-based unit hydrograph to compute transformation, and recession to estimate baseflow. The initial parameters inputted to the HEC-HMS are shown in Table 4.

Table 4. The initial parameters in HEC-HMS analysis

| Model Parameters                  | Welaran Watershed |
|-----------------------------------|-------------------|
| Watershed                         | 11.616            |
| Loss                              | CN AMC II         |
| SCS-Curve Number                  | CN AMC III        |
| Transformation                    | Impervious Area (%) |
| SCS Unit Hydrograph               | Lag Time (minute) |
| Baseflow recession                | Initial Discharge (m^3/s) |
|                                   | Recession constant |
| Source: HEC-HMS Model Analysis (2019) |
The modeling was conducted from November 18, 2018, to January 31, 2019. The simulation in HEC-HMS produced flow hydrograph and rainfall, which are presented in Figure 9. The results showed that during the period of observation, the highest peak discharge was 47.6 m³/s on December 18, 2018, at 05:10 PM. The other information gained from this model includes precipitation loss and baseflow.

Figure 9. The flow hydrograph generated by HEC-HMS

The peak time had difference in date or time of occurrence. It shows that the modeled hydrograph and the results of the field observation have no identical time. Time to peak is the time lag between the center of the mass of rain to peak discharge, which in this case was 84 minutes. The modeled and measured hydrographs have a similar shape, as depicted in Figure 10.

The generated model requires calibration because it does not have identical values to the measurement results in the field. In this study, the calibration was the trial and error method that lasted until the optimum modeling result was achieved. It involved five parameters, namely recession constant, threshold discharge, curve number, initial abstraction, and lag time. The curve number changed significantly from 67 to 42.89 and, accordingly, any values associated with soil humidity were also altered. In other terms, the calibrated model had reduced peak discharge but considerably exceeded the measured discharge in the field.
Although this step appears to have been successful in calibrating one flood event, it may not apply to runoff events that naturally have different characteristics. In some instances, the rainfall data produce a model that nearly mimics the results of the observation. Therefore, further review and research about the properties of the regional rainfall and the generated runoff become necessary.

4. Conclusion
The rainfall-runoff characteristics are depicted with hydrographs that have a tapered point. The hydrograph of Welaran Watershed has a fast peak time with a steep rising limb but relatively sloping or longer recession time. Based on the SCS-CN modeling, the curve number is 67 and the peak discharge and volume are 47.6 m$^3$/s and 63,126 (1000 m$^3$). The peak discharge has a lag time of 84 minutes. The modeled and measured hydrographs have a significant difference in peak discharge; therefore, calibration has been performed on the modeled hydrograph. It involves modifying the input parameters of HEC-HMS and rainfall and has successfully yielded a peak discharge that is close to the one measured in the field.

In some rainfall-runoff events in Welaran Watershed, the curve numbers derived through the unit hydrograph method vary between 23-82 for eight selected rainfall events. It indicates that there are many factors playing a role in the diversification of rainfall-runoff characteristics in a watershed, such as the actual distribution of rain. Also, AMC appears to depend not only on the amount of previous rainfall but also other factors that need further analysis.

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