Simulation of Rainfall-runoff process using HEC-HMS model for Garang Watershed, Semarang, Indonesia

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Abstract. Discharge data is one of the important data in evaluating the reliability of water resources management in the watershed. Most watersheds in Indonesia do not have observed discharge data over a long period. While the availability of rainfall data is almost available in all watersheds with a much longer period. Therefore, it is necessary to convert rain into a runoff to obtain a discharge event with a long period. Rain-runoff transformation is a very complex process. Rain input contains the variability of space, time and uncertainty. A very complex hydrological analysis is needed to find out various parameters related to rain models for a runoff. One of the hydrological models that can be used is HEC-HMS 4.2. This paper aims to analyze the relationship of rainfall - runoff in the Garang watershed using HEC-HMS 4.2. For calibration, observational discharge data is used from AWLR Kreo. Based on optimization analysis, the hydrological parameter are obtained CN composite 66.4, groundwater content 128.48 mm, Initial Abstraction 25.7 mm and imperviousness 9.27%. The validity of the model is quite satisfactory, judging from the correlation values, RMSE and Nash.

1. Introduction
The hydrological model is a simple presentation of the hydrological system in the watershed. This model aims to describe the response of a watershed to the hydrological processes that occur when given certain inputs. In the preparation of the hydrological model, the focus of the analysis is focused on the process of diversifying rain into flows through the watershed system. One of the hydrological models that can be used to diversify rainfall into streams (both flow events and continuous flow) is HEC-HMS (Center for Hydrological Engineering - Hydrological Modeling Systems, US Army Corps of Engineers). The purpose of this study was to analyze the relationship of rain runoff in the Garang watershed using the HEC-HMS 4.2 model. The hydrological modeling results are the hydrological parameters of the Garang watershed based on current land use data. The hydrological parameters of the soil discussed in this study consisted of a curve number (CN), initial abstraction and watertight. Land hydrological parameters can then be used to evaluate watershed management, especially related to future land use and allocation. This research is important because the Garang River is one of the raw water sources of Semarang City. Information about the potential changes in water availability due to the use of land use is very important so that steps can be taken early on.

2. Method of Study
The methodology can be divided into four major tasks: (1) obtaining the geographic locations of the studied basins; (2) DEM processing, delineating streams and watershed characteristics, terrain
processing, and basin processing; (3) importing the processed data to HMS; and (4) merging the observed historical data with the processed DEM for model simulations. [3]

2.1. The HEC-HMS Model
In HEC-HMS, rainfall runoff which is happening in the watershed is described into six major components i.e. meteorological component, loss component, direct runoff component, baseflow component, routing component, and reservoir component. For developing an HEC-HMS project needed four main contains the hydrologic elements (Sub-basin, reach, junction, reservoir, diversion, source, and sink) and their connectivity that represents the movement of water through the drainage system. Control specifications manager is one of the main components of the project and is principally used to control the time interval of simulation. As the first element for computing is the meteorological component. The meteorological component can be consist of time series of rainfall data and, evapotranspiration data. As the input of the model HEC HMS, needed basin rainfall data in the shape of time-series of precipitation data. For calibration a set of time-series of observed discharge data also required. The other input is component of climatological which consist of evapotranspiration. The HEC HMS process generally described in Figure 1.

![HEC-HMS Processes](image)

Figure 1. HEC-HMS Processes

The calculation method can be used in Table 1 below.

| No | Model       | Methods          |
|----|-------------|------------------|
| 1  | Precipitation | User Hyetograph  |
| 2  | Transformation | SCS’s UH    |
| 3  | Baseflow     | Exponential Recession |
| 4  | Routing      | Lag              |
2.2. **Methods for Calculating Runoff Volume with HEC HMS**

The waterproof layer is the part of the watershed that contributes to direct runoff without calculating infiltration, evaporation or other types of volume loss. While the fall of the water in the waterproof layer is also runoff. In HEC-HMS modeling, there are several runoff calculation methods that we can use, namely:

1. The initial and constant-rate loss model,
2. The deficit and constant-rate loss model,
3. The SCS curve number (CN) loss model (composite or gridded), and
4. The Green and Ampt loss model.

Because of the limited availability of field data needed in the use of the calculation methods mentioned above, the authors chose the SCS curve number (CN) method which is considered the easiest to apply in calculations.

2.3. **Synthetic Unit Hydrograph Calculation Method**

In modeling using HEC-HMS, there are several choices of methods that can be used to calculate unit hydrographs. The methods available include (HEC-HMS Technical Reference Manual, 2000: 56):

1. Snyder synthetic unit hydrograph
2. SCS (Soil Conservation Service) unit hydrograph
3. Clark unit hydrograph
4. Modified Clark unit hydrograph
5. Kinematic Wave unit hydrograph

The SCS Model Hydrograph Unit is a dimensionless Hydrograph Unit, which is achieved by a single peak Hydrograph Unit. SCS states that the peak Hydrograph Unit and peak time of the Hydrograph Unit are related by:

\[ U_p = C \frac{A}{T_p} \]  \hspace{1cm} (1)

Where \( A \) = watershed; and \( C \) = fixed conversion (208 in SI and 484 in leg system). The peak time (also known as the increased time) is related to the unit period of excess rain, such as:

\[ T_p = \frac{M}{2} + t_{lag} \]  \hspace{1cm} (2)

Where \( t \) = the duration of excess rain and \( t_{lag} \) = the time difference between the center of mass from the excess rainfall and the peak of the Hydrograph Unit. It should be noted that for \( t \), less than 29% of the total must be used [1].

When the time of the delay is set, HEC-HMS solves the equation to find the time from the top of the Hydrograph Unit and to find the peak of the Hydrograph Unit. The modified SCS equations to suit Indian conditions are as follows [4]:

\[ Q = \frac{(P-I_a)^2}{(P+0.7S)} \]  \hspace{1cm} (3)

\[ S = \frac{24500}{CN} - 254 \]  \hspace{1cm} (4)

\[ CN_w = \frac{CN + A_i}{A} \]  \hspace{1cm} (5)

Where:
- \( Q \) is runoff depth, mm; \( P \) is rainfall, mm; \( S \) is potential maximum retention, mm; \( I_a \) is 0.3 \( S \) (Initial abstraction of rainfall by soil and vegetation, mm); \( CN \) is Curve Number; \( CN_w \) is Weighted Curve Number; \( CN_i \) is Curve number from 1 to number of lands uses, \( N \); \( A_i \) is area with curve number \( CN_i \); \( A \) is total area of the watershed, and \( i \) is an index of the micro-watershed.
2.4. Determination of Curve Numbers (Curve Number, CN) and Impervious Area

SCS has developed a soil classification system into four soil hydrological groups (Hydrologic Soil Group = HSG). The soil properties based on the HSG grouping are listed in Table 2 that show the estimation value of CN based on land use and hydrologic soil groups. The value of CN can be determined using one of the following three methods: (a) based on soil properties, (b) detailed soil maps, (c) minimum infiltration rate. Table 3 presents the relationship of the minimum infiltration rate with each soil group.

Table 2 Hydrology Soil Group According to SCS and Its Characteristics

| Sl No | Land use      | Runoff curve numbers for hydrologic soil group |
|-------|---------------|-----------------------------------------------|
| 1     | Agricultural land | A     | B     | C     | D     |
| 2     | Barren land    | 59    | 69    | 76    | 79    |
| 3     | Built-up area  | 71    | 80    | 85    | 88    |
| 4     | Canal          | 77    | 86    | 91    | 93    |
| 5     | Forest         | 100   | 100   | 100   | 100   |
| 6     | Plantation     | 26    | 40    | 58    | 61    |
| 7     | River          | 51    | 100   | 100   | 100   |
| 8     | Scrub land     | 57    | 55    | 69    | 73    |
| 9     | Tanks          | 100   | 100   | 100   | 100   |

Note: Soil A – High infiltration; Soil B – Moderate infiltration; Soil C – Low infiltration; Soil D – Very low infiltration [4]

Table 3 Relationship between Minimum Infiltration Rate and Hydrologic Soil Group According to SCS (source: [5])

| Soil Group | Minimum Infiltration Rate (mm/hr) |
|------------|-----------------------------------|
| A          | 203.2 – 304.8                     |
| B          | 101.6 – 203.2                     |
| C          | 25.4 – 101.6                      |
| D          | 0.0 – 25.4                        |

In determining the state of the soil moisture content (SMC) previously it was often used the average state of the flow area at a particular place and time SCS prepares three previous soil moisture content states as follows [4]:

Condition I: The soil is dry but does not reach the point of wilting, has been planted with satisfactory results.
Condition II: Average state.
Condition III: Heavy or light rain and low temperatures have occurred in the last five days; the soil is saturated with water.

SCS provides a limit on the amount of rainfall for each of the previous soil moisture content conditions as in Table 4. Calculation of the rain-runoff process is considered to take place in the growing season.

Table 4 Limitation of Amount of Rainfall in Every Previous SMC Condition.

| Condition | Total rainfall five days before (mm) |
|-----------|-------------------------------------|
|           | Dormant season | Growing season |
| I         | < 13           | < 35           |
| II        | 13 – 28        | 35 – 53        |
The value of the curve number for the previous SMC condition in condition II follows the table presented by SCS. The value of the curve number for the previous KAT conditions in conditions I and III is calculated using the equation as follows [7]:

\[
CN (I) = \frac{4,2CN (II)}{10 - 0,058CN21 (II)}
\] (6)

and,

\[
CN (III) = \frac{23CN (II)}{10 + 0,13CN (II)}
\] (7)

For watersheds consisting of several types of land types and land use, the value of the curve number is set as the composite value. The composite curve number is determined based on the broad weighted form of land use in the watershed (USACE 2001)

\[
CN_{composite} = \frac{\sum_{i=1}^{n} A_i \cdot CN_i}{\sum_{i=1}^{n} A_i}
\] (8)

where \(CN_{composite}\) is the number of the combined curve for the entire watershed, \(I\) states the index for the I subdivision.

In addition to curve numbers, the parameters that also affect the runoff volume of a watershed are the area of impervious regions. Impervious area of a watershed is the area of a watershed where all contributions from precipitation will become direct runoff without experiencing infiltration, evaporation or other forms of water loss [1].

2.5. Calibration phase

This stage is the stage used to determine the unknown watershed parameter values. In the calibration process, the initial values are considered valid for all parameters and the flow period is simulated and compared with measured discharge. If it is needed, the parameters are changed and the comparison is repeated until satisfactory conformity is obtained between the observation data and the calibration results data. The scheme of the calibration process is shown in Figure 2.

![Figure 2 Schematic of the Calibration Process [6]](image-url)
2.6. Validation and Verification Phase
The verification phase is needed to ensure that the calibration result parameters can represent the characteristics of the actual watershed. Verification is a calculation process using input data other than those used in the calibration stage but uses the watershed parameters generated in the calibration stage. The validation process in a modeling calculation such as HEC-HMS is very important. This validation is intended to carry out the process of checking the output of HEC-HMS on the data available in the field. In this validation process, it is expected to be able to determine the value of the parameters of the watershed characteristics such as CN (Curve Number), initial recharge (Initial Abstraction), imperviousness or baseflow value so that finally get the results closest to conditions in the field. To determine the validation of the model, between the simulation results and observations discharge there are several methods such as RMSE and the Nash method [8]. In this study, the validation of the model used the Nash method.

2.7. Tools and Material
Tools and material which are used in this research consist of daily rainfall data, Daily observed flow, Land-use maps, Map of digital elevation and Soil map and its characteristics.

2.8. Study Field Description
Garang watershed has an area of about 212.77 km², divided into four (4) sub-watersheds, namely Garang Hulu watershed (83.71 km²), Kreo watershed (68.56 km²), Kripik watershed (36.47 km²) and the remaining catchment are Garang Hilir watershed or West Flood Canal.

2.9. Type of soil
The soil types of Garang watershed was obtained from the Pemali Jratun Watershed Management Agency, Central Java Province. The soil types in the Garang watershed are dominated by latosol and regosol soils, while the rest are alluvial, grumusol and Mediterranean. In the sub-section of the Upper Garang watershed, it is dominated by latosol and regosol soils with few grams and Mediterranean. Similarly, the Kreo and Kripik watersheds. Alluvial and mediterranean types dominate the Lower Garang sub-watershed.

2.10. Garang watershed land use
In this study using two conditions of land use, namely 2016 land use and Spatial Planning of Central Java Province for the year of 2011-2030.

2.10.1. Land Use 2016
Based on the Citra Map processed by Watershed Management Agency of Pemali Jratun in 2016 that 36% of the area of the Garang River Basin is plantations, 21% of rice fields, 19% of settlements, 10% of forests, 6% of fields, 5% of bushes, 3% of savannas and 0.11% of rivers as in Figure 3.

2.10.2. Land use is based on the 2030 Spatial Planning map
When compared to the existing land use in 2016 with land use, the RTRW changes. The most significant changes in land use occur in settlements, plantations, and forests. While reduced land use is paddy fields, dry fields, and savannas. Area of Settlements in 2016 amounted to 4051.36 hectares (19%) and based on residential area RTRW of 7292.94 hectares (34.3%) or an increase of 15.24%. This has an impact on rainwater, which will become more surface flow due to the ability of infiltration into the soil to be smaller and the runoff coefficient to be even greater. The use of plantation land has also increased by 4.75%; land use has increased by around 0.58%. While the use of paddy fields decreased by 10.37%, the fields experienced a reduction of 5.66%, and savannas experienced a reduction of 3.25%.

2.11. Hydrological Modeling of Garang Watershed
Modeling of Garang watersheds is shown in Figure 4. With the catchment characteristic of each sub-basin, and rainfall-runoff transformation method used SCS method with daily rainfall there can be calculated runoff at any point wanted to be reviewed.

2.12. Model Simulations

As the initial input of the model is regional rainfall data obtained from several rain posts in or around the Garang watershed. Rain gauge stations in the Garang watershed are Kalisari, Gunungpati, Sumurjurang, and Bendongan Simongan. Rainfall data which used for calibrating of watershed hydrological parameters are data in 2013. In the analysis the observational discharge data is used data from the AWLR Kreo, remembering sufficiently complete data between rain data and discharge data at the same time. Data processing carried out included regional rainfall analysis using the polygon Thiessen method. Analysis of CN values is based on watershed characteristics such as land, vegetation, and land use. In addition to the curve number (CN), the area of imperviousness also influences runoff volume from a watershed. Impervious area of a watershed is the area of a watershed where all contributions from precipitation will become direct runoff without experiencing infiltration, evaporation or other forms of water loss.

3. Result and Assessment

Rainfall-Runoff Simulation of Kreo Sub-watershed was used in 2013 data, because in the year in the rain data and observed discharge data are the most complete daily data. From the results of the data that has been input into the HEC-HMS using parameters optimized in the Kreo Sub-watershed, it is presented in the form of a hydrograph as shown in Figure 5.
The hydrograph above compares the observed flow (Q observed) with the modeled flow. Comparison of the results of validation discharge can be seen in Table 5.

| Parameter                  | Model     | Observation | Difference | % Difference |
|----------------------------|-----------|-------------|------------|--------------|
| Total Outflow (1000 m³)    | 73267.1   | 78703.5     | 5706.4     | 7.3          |
| Peak Flow (m³/sec)         | 16.6      | 19.5        | 2.9        | 14.8         |

The model simulation results can be seen from the similarity of hydrograph between the measured discharge and the model discharge. The quality of the model can also be seen from the pattern or fluctuations in the flow of simulation results that can be expressed by the correlation coefficient. This correlation coefficient is made to pair data from the simulation model with observational data. In a simulation with a CN value of 50.4 and the value of initial abstraction 49.94, it is obtained that the model correlation coefficient of the simulation results with observational data is 0.56. Furthermore, in the simulation with a CN 66.4 value and the value of initial abstraction 25,697, the model correlation coefficient value with observational data is 0.64. The correlation coefficient value is closer to number 1. So in the simulation of Kreo sub-watershed, a CN value of 66.4 is used. Quantitatively, the reliability of the model can be statistically assessed with various benchmarks and criteria including RMSE and Nash. In the 2013 Kreo sub-watershed simulation model the RMSE error value was 47.58, while the Nash value was 64.35. This Nash value falls into the range 75 > NS > 36 so that the simulation model is categorized as satisfactory. Using land change data based on the RTRW map in 2030, the parameters of the Garang watershed can be estimated. The final results of optimizing the hydrological parameters of Garang watersheds using the HEC-HMS model are shown in Table 6.

| Items                  | Existing (2016) | RTRW (2030) |
|------------------------|-----------------|-------------|
| CN composite           | 66.4            | 69          |
| S (mm)                 | 128.48          | 114, 12     |
| Initial Abstraction (mm)| 25.7            | 22.8        |
4. Conclusion
The results of this study known that the HEC HMS model is good enough to be used to model rain-runoff in the Garang watershed. Using the current land use with model calibration using data from 2013 it is known that the hydrological parameters for HEC-MHS were obtained, namely CNcomposite values of 66.4, groundwater content 128.48 mm, Initial Abstraction 25.7 mm and imperviousness 9.27%. Based on the hydrological parameters of the watershed, the validity of the model is quite satisfactory, judging from the correlation values, RMSE and Nash. Furthermore, by using land use from the spatial planning map in 2030 is estimated that hydrological parameters for the Garang watershed are CNcomposite values of 69, groundwater content (S) 114.12 mm, Initial Abstraction 22.8 mm and imperviousness 17.75%. The Increased of CN values and imperviousness, and decreases of groundwater content and initial abstraction values have increased the amount of runoff which has an impact on increasing flood discharge and decreasing low discharge which has an impact on decreasing water availability.

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References
[1] USACE. 2000. Hydrologic Modelling System HEC HMS Technical Reference Manual. Maret 2000. http://www.hec.usace.army.mil.
[2] USACE. 2002. Hydrologic Modelling System HEC HMS Applications Guide. December 2002. http://www.hec.usace.army.mil.
[3] USACE. 2000. Geospatial Hydrologic Modelling Extension HEC GeoHMS Users Manual. Juli 2000. http://www.hec.usace.army.mil.
[4] Kumar, P., Tiwari, K. N. and Pal, D. K. 1991. Journal of the Indian Society of Remote Sensing. 19 (4) 245 – 251
[5] McCuen, R.H., (1982), “A guide to hydrologic analysis using the SCS Methods:” Englewood Cliffs, N.J., Prentice-Hall, 145 p.Moore, I. D., R. B. Grayson, and A. R. Ladson. 1991., “Digital Terrain Modeling: A Review of Hydrological, Geomorphological and Biological Applications.” Hydrological Processes. 5 (1) 3-30
[6] Bulcock, H. and Jewitt, G. 2010. Hydrological modeling system, hec-hms user's manual. Hydrology and Earth System Sciences. 14 (2) 383-392.
[7] Chow, V. T., D. R. Maidment and L. W. Mays. 1988. Applied Hydrology. 572
[8] Drogue G., Pfister L., Leviandier T., El Idrissi A., Iffly J.F., Matgen P., Humbert J., Hoffmann L. 2004. Journal of Hydrology. 293 255–269