Gajahwong River Continuous Flow Simulation by Using Soil Moisture Accounting (SMA) of HEC HMS

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Abstract. Gajahwong River is located in the southern part of Java Island, Indonesia, specifically on Daerah Istimewa Yogyakarta. Gajahwong River has an important role along the area where its discharge is used especially for irrigation water supply. Other factors stressing Gajahwong basin's water supply purpose are population number rise and land cover change that influence river streamflow in the whole year. Hence, a continuous flow simulation was conducted to analyze Gajahwong River water availability to supply its requirement. The Soil Moisture Accounting (SMA) module of HEC-HMS was employed to simulate the continuous flow of Gajahwong River, particularly in Wonokromo Outlet. The continuous flow was simulated from the year 2012 until 2015 based on observed discharge data availability. Comparison between simulated and observed discharge was quantified by using R2, Nash-Sutcliffe efficiency and PBIAS statistic value. The statistic above parameter values yielded a value of 0.90, 0.58, and 2.02%, respectively for daily time series simulation.

Keywords: flow simulation, irrigation, water supply

1. Introduction
Gajahwong basin stretches from Mount Merapi in the northern area of Daerah Istimewa Yogyakarta, located in Java Island until the Wonokromo area in the southern part. Gajahwong basin size area is ± 49.08 km², and Gajahwong river length is ± 22.81 km (see figure 1). Gajahwong river flows along area that experiences high development rate in Yogyakarta such as Kabupaten Sleman, Kota Jogjakarta, and Kabupaten Bantul. Area development and land cover conversion influence the amount of rainfall volume infiltrating into the soil; thus infiltration rate will cause a change in the amount of groundwater reserve. On the other hand, Gajahwong river has a major role in irrigation water sources for irrigation areas along its river reach. Hence, streamflow simulation is needed to analyze water balance in determining cultivation patterns because of the limitation of water availability.

HEC-HMS software, specifically the Soil Moisture Accounting (SMA) module, was widely used for river streamflow simulation. The researchers showed various statistical parameter results to compare observed and simulation data to assess simulation result performance. Soil Moisture Accounting SMA module was applied for simulating the continuous flow of Jhelum River catchment in Western Himalaya, where the NS value of simulation was 0.68 [1]. A similar hydrology module was employed in Vamsadhara River Basin in India. The simulation results showed that the value of R2 was 0.71 and NS value was 0.701 for the calibration process, while for the validation process value of R2 was 0.78 and NS was 0.762 [2]. The simulation also determined parameter sensitivities, soil storage was the most sensitive parameter, and GW2 was the least sensitive parameter. HEC-HMS SMA module was applied to simulate the Upper Blue Nile River Basin [3]. The simulations
were divided into four catchment areas. Findings yielded various values of both statistical parameters NSE and $R^2$. NSE value ranged from 0.49 to 0.78, whereas the $R^2$ value was between 0.5 and 0.78. HEC-HMS SMA model was used to model the Lower Colorado River continuous flow [4]. Results showed that the Nash-Sutcliffe efficiency value was 0.71, while the coefficient of determination value was 0.74. HEC-HMS SMA module was used to model Mkurumudzi River Catchment streamflow in Kenya [5]. Findings showed that both NSE and $R^2$ value for calibration process was higher than validation process. The value plummeted from 0.8 to 0.65 for the NSE value, whereas the $R^2$ value dropped from 0.80 to 0.67.

2. Materials and Methods

2.1 Area rainfall intensity analysis
The magnitude of area rainfall intensity was calculated by using the polygon Thiessen method. The weighted factor representing the influence percentage of each rainfall station is determined based on the size area of each polygon in Gajahwong River Basin. Then, the rainfall intensity result is applied as an input in HEC-HMS software to perform the simulation in daily time series.

2.2 Land cover analysis
Landsat image was employed in land cover classification analysis to the determined land cover classification of Gajahwong River Basin. HEC-HMS needs information regarding the size of the water body to perform hydrology model simulation.

2.3 HEC-HMS
HEC-HMS is a hydrology model developed by the US Army Corps of Engineers. The hydrology model can simulate event flood discharge and streamflow discharge [6]. In performing streamflow simulation, one can use Soil Moisture Accounting (SMA) module for loss analysis. The module simulates water
motion and amount of water in canopy storage, storage on the soil surface, soil profile storage, and groundwater by employing a tank model. Moreover, the SMA module can simulate both surfaces runoff and baseflow. The SMA module is derived from coinciding similar hydrology behaviour in natural conditions. Several parameters characterize as tank models need to be optimized in the calibration process. The concept of the SMA module is illustrated in figure 2.

Below are explanations of the water flow process involved in hydrology simulation by using the SMA module.

1 Canopy interception represents the vegetation aspect in the basin model. The canopy interception shows leaves' ability to hold rainfall water; thus, it will not directly drop on the soil surface. In HEC-HMS, this process is represented by the canopy method.
2 Part of rainfall water that is not retained by leaves will drop on the soil surface. If soil moisture is not saturated, dropping water can infiltrate into the soil until it fills surface storage fully. While soil moisture condition is saturated, rainwater can inundate in surface depression. The method in simulating surface storage can be determined in the surface method. Part of rainfall that is not contained in this layer will become baseflow.
3 The lower layer is soil storage that consists of the upper zone and tension zone. An upper zone contains water filling air cavity, yet water does not merge with soil material. Water that fills the upper zone can percolate into the lower layer. The tension zone has a different characteristic, and the water filling tension zone is assumed to merge with soil material. Hence, tension zone water can evaporate, but it cannot percolate.
4 Percolated water from the upper zone layer can flow into groundwater layer one storage. In this layer, water can move horizontally and become groundwater. When the groundwater capacity is full, the excess water will flow into groundwater layer two storage. Characteristic of groundwater layer two storage is similar with upper layer characteristic.

HEC-HMS divides hydrology simulation into five processes: analysis of canopy storage, surface water storage modelling, rainfall loss method, rainfall transformation, and baseflow simulation. For each hydrological process, HEC-HMS provides several methods to analyze the fit between the hydrological model and real conditions. Another important aspect in selecting each applied method was data availability. Methods applied in every hydrology process are listed in Table 1.

2.4 Statistic parameter
Several statistic parameters such as Nash Sutcliffe efficiency (NSE), coefficient determination (R²), and percent bias (PBIAS) were suggested to measure the quality of hydrology simulation [7]. Moreover, [7] also suggested quality classification of hydrology modelling results based on these statistic parameters (see table 2).

Firstly, Nash Sutcliffe efficiency (NSE) compares the relative magnitude of the residual variance toward measured data variance in the normalized statistics. Moreover, the NSE also illustrated how well observed data and measured data will fit the 1:1 line. NSE value ranges from −∞ to 1.0, with NSE = 1.00 is the optimal value. NSE range from 0.00 until 1.00 indicates acceptable performance level, while NSE value ≤ of 0.00 shows unacceptable performance level.

Secondly, R² illustrates how simulation data explains the variance proportion of measured data. R² ranges between 0.00 and 1.00; a higher R² value shows less error variance.

Finally, PBIAS gives information regarding the average tendency of simulation data toward observed data, whether the simulation data is higher or lower than the counterpart of observed data. The optimal PBIAS value is 0.00, with a positive value shows an overestimate bias; on the other hand, a negative value indicates bias.

\[ R^2 = \left( \frac{\sum (Q_{m,i} - Q_{m,avr})(Q_{s,i} - Q_{s,avr})}{\left( \sum (Q_{m,i} - Q_{m,avr})^2 \sum (Q_{s,i} - Q_{s,avr})^2 \right)^{0.5}} \right)^2 \] (3)
\[ NSE = 1 - \frac{\sum_i (Q_m - Q_s)^2}{\sum_i (Q_m - Q_{m,avr})^2} \]  

\[ PBIAS = \left[ \frac{\sum_{i=1}^{n} (Y_{i,obs} - Y_{i,sim})}{\sum_{i=1}^{n} Y_{i,obs}} \right] \times 100 \]  

Where \( Q_m \) is observed river discharge (m\(^3\)/second), \( Q_{m,avr} \) is mean observed river discharge (m\(^3\)/second), \( Q_s \) is modelled river discharge (m\(^3\)/second), and \( Q_{s,avr} \) is mean modelled river discharge (m\(^3\)/second).

**Figure 2.** Concept of soil moisture accounting module in HEC-HMS

**Table 1.** The selected method in each hydrology process

| Hydrology process | Analysis method                  |
|-------------------|----------------------------------|
| Canopy method     | Simple canopy                    |
| Surface method    | Simple surface                   |
| Loss method       | Soil moisture accounting (SMA)   |
| Transform method  | Clark unit hydrograph            |
| Baseflow          | Linear reservoir                 |

**Table 2.** Performance criteria classification [7]

| Statistic parameter | Performance criteria |
|---------------------|----------------------|
| R\(^2\)             | Very Good: R\(^2\) > 0.85  
                        | Good: 0.75 < R\(^2\) ≤ 0.85  
                        | Satisfactory: 0.60 < R\(^2\) ≤ 0.75  
                        | Not satisfactory: R\(^2\) ≤ 0.60 |
| NSE                 | Very Good: NSE > 0.80  
                        | Good: 0.70 < NSE ≤ 0.80  
                        | Satisfactory: 0.50 < NSE ≤ 0.70  
                        | Not satisfactory: NSE ≤ 0.50 |
| PBIAS (%)           | Very Good: ±5  
                        | Good: ±5 ≤ PBIAS ≤ ±10  
                        | Satisfactory: ±10 ≤ PBIAS ≤ ±15  
                        | Not satisfactory: PBIAS ≥ ±15 |
2.5 Data
There were point data and raster data that were used to simulate Gajahwong River streamflow. Point data were rainfall data, climatology data, and discharge data acquired from AWLR station that is acquired from Balai Besar Wilayah Sungai Serayu Opak of General Work and Housing Ministry [8]. At the same time, raster data used for simulation was digital elevation model and Landsat image. Below are explanations regarding data applied for simulation.

1. The rainfall data were acquired in four rainfall stations (see table 3). The climatology data was acquired from the Playen climatology station [8].
2. The outlet location for this hydrology simulation is the location of AWLR station downstream of Gajahwong River, precisely in Wonokromo AWLR station. Discharge data were derived by employing a rating curve equation in AWLR station location [8].
3. ALOS PALSAR DEM was used for the digital elevation model. The digital elevation model was applied for watershed delineation by using GIS software. The function of DEM in this analysis is mainly in determining the size area of the watershed [9].
4. The Landsat 8 OLI imagery issued United States Geological Survey (USGS) [10].

3. Result and Discussion

3.1 Area rainfall intensity
Polygon Thiessen of rainfall station was used to the determined percentage of employed rainfall station in calculating area rainfall intensity. From the polygon Thiessen, it was obtained that the rainfall station has the biggest influence was Prumpung, while the rainfall station that had the lowest weighted factor was Kemput (see table 3).

| Rainfall Station | Latitude | Longitude | Elevation (m) | Weighted factor |
|------------------|----------|-----------|---------------|-----------------|
| Bedugan          | -7,86    | 110,40    | 18            | 25.09%          |
| Santan           | -7,78    | 110,42    | 118           | 31.00%          |
| Prumpung         | -7,70    | 110,39    | 575           | 37.94%          |
| Kemput           | -7,64    | 110,40    | 575           | 5.96%           |

3.2 Land cover analysis
The land cover classification analysis by employing Landsat imagery gave information that water body percentage was 2.32% of Gajahwong River Basin size area. Map as land cover classification analysis was illustrated in figure 3. The percentage value of each land cover type can be read in Table 4.

| No | Land cover   | Percentage (%) |
|----|--------------|----------------|
| 1  | Forest       | 0.61%          |
| 2  | Agriculture  | 37.61%         |
| 3  | Urban        | 52.18%         |
| 4  | Pasture      | 0.37%          |
| 5  | Range        | 1.24%          |
| 6  | Shrubland    | 5.67%          |
| 7  | Water        | 2.32%          |
|    | Total        | 100%           |
3.3 Parameter optimization
Numerous parameters influenced the continuous flow simulation process. Based on the selected process option, 21 parameters must be optimized to coincide simulation discharge with observed discharge. The optimization process was very challenging. In HEC-HMS, there are two methods to optimize parameter values. The most popular method and employed by many researchers are the optimization method supported by HEC-HMS. However, this method is confusing, notably for those who use the optimization method first. They usually optimize many simulation parameters at one time. Therefore optimized value will be difficult to be obtained.

The last method was the trial and error process by inputting parameter values manually. This analysis was employed the last method. The advantage aspect of this method is that one can enhance understanding of parameter characteristics toward the hydrology model. The optimized parameter value achieved for continuous flow simulation of Gajahwong River can be seen in table 5.

3.4 Streamflow simulation
The optimized parameter value for continuous flow simulation was applied for a four-year series simulation from 2012 to 2015. The simulation was committed for daily simulation (see figure 4). Overall, in the first year of simulation, the discharge shows fluctuation simulation discharge. In the early simulation time, it can be identified that the hydrology model saw turbulence when the simulation was started at the near end of the rainfall season. The turbulence can occur because it is common that the hydrology model in the early simulation is started by using estimated initial conditions.

Moreover, the hydrology model will also be more stable with more simulation time because each model parameter will approach real conditions. Furthermore, the simulation discharge experienced

Figure 3. Landcover map of Gajahwong River Basin
stability that it started to simulate better in responding to the dry season. Nevertheless, the model simulation still inhibits the lack of modelling fluctuation discharge, particularly in the rainfall season.

**Table 5. Optimized parameter value**

| No  | Parameter                  | Unit     | Optimization value |
|-----|----------------------------|----------|--------------------|
| 1   | Initial storage            | %        | 1                  |
| 2   | Max storage                | mm       | 1                  |
| 3   | Initial storage            | %        | 50                 |
| 4   | Max storage                | mm       | 1                  |
| 5   | GW1 percolation            | mm/hour  | 1.5                |
| 6   | GW1 storage                | mm       | 100                |
| 7   | GW1 storage coefficient    | hour     | 50                 |
| 8   | GW2 percolation            | mm/jam   | 1.5                |
| 9   | GW2 storage                | mm       | 100                |
| 10  | GW2 storage coefficient    | jam      | 50                 |
| 11  | Initial GW1 content        | %        | 100                |
| 12  | Initial GW2 content        | %        | 100                |
| 13  | Initial soil content       | %        | 100                |
| 14  | Max infiltration           | mm/jam   | 1.5                |
| 15  | Soil percolation           | mm/jam   | 1.5                |
| 16  | Soil storage               | mm       | 400                |
| 17  | Tension storage            | mm       | 25                 |
| 18  | Time of Concentration      | hour     | 24                 |
| 19  | Storage Coefficient        | hour     | 100                |
| 20  | GW1 Initial                | m³/second| 0.75               |
| 21  | GW1 Fraction               |          | 1                  |
| 22  | GW1 Coefficient            | hour     | 1                  |
| 23  | GW1 Steps                  |          | 3                  |
| 24  | GW2 Coefficient            | hour     | 100                |
| 25  | GW2 Steps                  |          | 6                  |

Overall, along simulation time from 2012 until 2015 statistic parameter gives 2.02% of PBIAS, 0.58 of NSE, and 0.90 of $R^2$ value. Based on [7], the simulation parameter statistic can be classified as very good for $R^2$ and PBIAS, while the NSE value can be concluded as satisfactory. The comparison between observed discharge and simulation discharge from the year 2012 to the year 2015 is illustrated in figure 4.

Statistical parameters were also analyzed for each year. All statistical parameters fluctuated along the simulation year. In every year, the $R^2$ parameter can be qualified as very good that the value was 0.91, 0.88, 0.91, and 0.89 sequentially. NSE value grew better, yet the statistic value was still qualified as not satisfactory. From the year 2012 to 2014, the NSE value was 0.26, 0.49, and 0.36, respectively. Overall, last year’s simulation can be classified as satisfactory that the NSE value rose slightly to 0.51. Initially, the PBIAS value in the year 2012 was 14.58% that can be qualified as satisfactory. Then the
qualification was very good in 2013 and 2014, which was -2.66% and 4.91%. Finally, in 2015 the PBIAS value slipped slightly to 5.34% that can be classified as good.

Figure 4. Comparison of simulated discharge and observed discharge

4. Conclusion
To sum up, simulation of Gajahwong River continuous flow using the SMA module of HEC-HMS gives good qualitative judgment. However, the simulation still has limitations in modelling fluctuate daily discharge. For future analysis, it is suggested to simulate the continuous flow by employing the spatial feature offered by the newest version of HEC-HMS. It is hoped that by applied spatial based simulation, the effect of spatial rainfall variability can enhance simulation results. More opportunity that can be maximized is the application of satellite-based rainfall data that can explore, especially in the ungauged area.

For the condition that there are just short observed discharge time series data, applying the same data as dummy initial condition is suggested to optimize simulation. Thus, all of the time series data can be used for simulation.

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