Numerical rainfall-runoff model of Cimanuk Watershed before and after the operation of Jatigede Reservoir

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Abstract. Cimanuk watershed is one of the watersheds in West Java that has critical land. Critical land resulted in a Cimanuk watershed becomes a flood and drought. The management of Cimanuk Watershed water availability is done by regulating water supply from the Cimanuk River with the conduction of Jatigede Reservoir. The watershed hydrological process is the relationship between inputs in the form of rainfall, process, and output in the form of runoff. The process of converting rainfall into runoff is very complex, therefore, simplifying the rainfall-runoff model approach is needed. Hydrologic Engineering Center-hydrologic Modeling System (HEC-HMS) is one of the models for simulating rainfall into runoff. The purpose of the study is to simulate the availability of water surface at Cimanuk Hulu watershed using HEC-HMS hydrological modeling system based on before and after the operation of Jatigede reservoir. The results showed that the calibration of the model produced an NSE value of 0.640. On the other hand, the best validation results was in 2018 with NSE of 0.576 with the peak discharge value before the operation of the reservoir was of 456,8 m\textsuperscript{3}/s, and after modified with the presence of Jatigede Reservoir, peak discharge became 131,9 m\textsuperscript{3}/s.

1. Introduction

Cimanuk watershed is one of the watersheds located in West Java within the working area of the Balai Besar Cimanuk-Cisanggarung. Geographically, Cimanuk Watershed is at 7,45° - 6,42° LS and 107,6° - 108,8° BT, while administratively, it is located in four districts, including Garut Regency, Sumedang Regency, Majalengka Regency, and Indramayu Regency. The total area of Cimanuk watershed is 3.216,14 km\textsuperscript{2} with Cimanuk river becomes the main river having a length of 258 km [1]. The Cimanuk river is an upstream in Garut Regency and a downstream in Indramayu Regency.

Based on information from the Cimanuk-Citanduy BPDAS in 2003, Cimanuk watershed has a critical land reaching 178,794 Ha on forest and non-forest area. The biggest critical land is in Garut Regency, reaching 90,045 hectares [2]. This critical land has caused worsening hydro-oro logical condition in the watershed. This can be seen from the very large discharge fluctuation in the Rentang Weir, \(Q_{\text{maks}} = 1.004 \text{ m}^3/\text{s}\) and \(Q_{\text{min}} = 4 \text{ m}^3/\text{s}\) [1].

The impact of the critical land in Cimanuk watershed is frequent flooding, drought, erosion, landslides, and sedimentation. The occurrence of flood in the Cimanuk watershed is a routine event that occurs both upstream and downstream of the watershed. The management of Cimanuk watershed water availability is carried out by the construction of Jatigede Reservoir. This reservoir is a multifunctional...
reservoir that aims to control flood, raw water supply, irrigation, and hydropower in Cimanuk Watershed.

Efforts to conserve Cimanuk watershed have been carried out by several researchers as well as policies and evaluations from the BBWS Cimanuk-Cisanggarung. Several studies have been carried out such as the research conducted by Santoso on the study of determining the priority sequence of the management of critical land in Cimanuk Hulu watershed using delphi method, resulting in the conclusion of increasing criteria for determining critical land priority [3]. Furthermore, regarding the geomorphological characteristics, Cimanuk watershed is composed of easily destroyed rocks which can increase the rate of erosion and cause siltation of Jatigede Reservoir [4]. In addition, a study has been conducted on the Cimanuk Hulu flood analysis caused by land use in a poorly precise area, high rainfall intensity, and population density in flood prone areas [5]. Research conducted by Pradwipa regarding the utilization of Jatigede reservoir as a surface water resource was carried out based on the history of Cimanuk river discharge which was on the basis on the upstream recording of the Jatigede reservoir on the use of the reservoir as the priority for irrigation and hydropower [6].

The watershed hydrology process is the relationship between input/inflow in the form of rainfall, process, and output in the form of runoff. The process of transforming rainfall into runoff is a very complex [7]. To simplify such a very complex process, a rainfall-runoff model approach is needed [8]. The rainfall-runoff model can predict the daily and monthly runoff value of a watershed based on the rainfall, evaporation, infiltration and watershed characteristic parameters. Hydrologic Engineering Center-hydrologic Modeling System (HEC-HMS) is one of the rainfall-runoff models developed by U. S Army Corps of Engineering. HEC-HMS simulates watershed hydrological processes by simplifying systems in nature based on watershed characteristics.

Based on research related to the condition of the Cimanuk watershed, it is necessary to analyze the use of Jatigede reservoir on the conservation of surface water resources in Cimanuk watershed. Therefore, this research used rainfall-runoff model on the availability of Cimanuk watershed in the conditions before and after the operation of Jatigede reservoir using the HEC-HMS rainfall-runoff model.

2. Research Method

2.1. Study Area
The location of this research is the Cimanuk Hulu watershed in the Cimanuk-Cisanggarung BBWS working area. The Cimanuk Hulu watershed which is the watershed of the Jatigede Reservoir in this study has an area of 1,457.26 km² and a river length of 105.1 km. The Cimanuk Hulu Watershed is dominated by a rather steep to steep area with a slope of > 15% [9]. The watershed is in the administrative area of Garut Regency and Sumedang Regency. Here, the Jatigede Reservoir becomes a multifunctional reservoir in optimizing the use of surface water in Cimanuk watershed. Jatigede Reservoir is located in Cijeungjing village, Jatigede District, Sumedang Regency. As a multifunctional reservoir, Jatigede reservoir is used for irrigation, hydropower, raw water, and flood control.

2.2. Research Data and Processing

2.2.1. Research Data
The data used in this research are hydrological, climatological, spatial data, profile of Jatigede Reservoir, Jatigede Reservoir capacity arch, and the profile of Cimanuk River. Hydrological data in the form of Cipasang post daily discharge data were obtained from BBWS Cimanuk-Cisanggarung. Daily rainfall data used in this study consisted of sta rainfall data from Sta. Jatigede, Sta. Bayongbong, Sta. Cikajang, and Sta. Leuwengtitis. The rainfall data were obtained from BBWS Cimanuk-Cisanggarung. Climatology data were obtained from BMKG online data that can be downloaded through the official website of BMKG (http://dataonline.bmkg.go.id/). Climatological data obtained were in the form of daily wind speed data, daily sun radiation, daily temperature data, and daily humidity data. Spatial data used were in the form of Digital Elevation Model (DEM) maps, land use map, and soil types maps.
2.2.2. Processing
The framework in this study begins with the collection of secondary data. Then, the secondary data is processed. Secondary data processing such as rainfall data, discharge data, and climatological data that are time series which are done by filling in the missing data first. To fill in the missing data, the normal ratio method is used, and the result is tested for the data consistency that has been corrected. After completing the time series data, then the data are processed data according to the data requirements entered in the HEC-HMS model. The rainfall data of each rainfall station are calculated to be the regional average using Thiessen method, while the climatology data are used to calculate the evapotranspiration value using Panman modification method.

After conducting secondary data processing, the model development is carried out using HEC-HMS. The structure of the development of the HEC-HMS model consists of six components in which there are various methods. Calculation that can be performed using HEC-HMS includes the precipitation model, runoff volume model, direct runoff model, baselayout model, search model, and water control model [10]. This study will use the calculation of the precipitation model using specified hyetograph, evapotranspiration by manual calculation using the Panman modification method, calculation of surface flow using SCS UH, calculation of baseflow using constant monthly, and the routing calculation on the channel using kinematic wave.

Development of the HEC-HMS model begins with the creation of basin model. This model consists of the created watershed elements such as rivers, junctions, reservoirs, sinks, sub-basins that are arranged to describe the physical representation of the watershed [11]. In the basin model, there are parameters that describe the watershed characteristics. The parameters used in the study include of Manning coefficient, Curve number (CN), LagTime, Initial abstraction, impervious, canopy, surface, and baseflow. Furthermore, it is also carried out the making time series data components containing discharge data, rainfall data, and evapotranspiration data needed in this study. The latter makes a paired data component in the form of storage discharge which is used when simulating the operation of Jatigede Reservoir on the model.

After building the model, it is ready in run and calibrates the parameters that affect the characteristics of the watershed in the field. After the calibration, modifications are made by adding reservoir to the model. Adding the reservoir is done by duplicating the Basin Model during the calibration, then
replacing Junction 12 elements into a reservoir. The results of the model before and after the operation of the reservoir were analyzed for the availability of surface water at Cimanuk Hulu Watershed.

![Figure 2. Basin model before the operation of Jatigede Reservoir](source)

Source: Analysis result

![Figure 3. Basin Model after the operation of Jatigede Reservoir](source)

Source: Analysis result

2.3. Calibration and Validation Model
Calibration is the process of selecting parameter combinations [12]. In principle, the model is able to provide responses that match expectations, but which models are able to present the conditions in nature. The output of the model is expected with data from field observation. In this study, the calibration was performed on the data discharge model for the observation of the discharge. The calibration model is carried out by trial and error. In this study, the calibration model was carried out on July 1, 2011 – December 31, 2014 on the recording of daily discharge in Cipasang post.

Validation is the process of evaluating the model to get a picture of the level of uncertainty in predicting the hydrological process. The data are used for the validation period using data outside of the calibration period data [12]. In this study, the data used for validation are data from Cipasang post discharge recording in 2016, 2017, and 2018.

To test the reliability of the model, this study used the Nash Sutcliffe Efficiency (NSE) test. The value of efficiency coefficient can range from infinite minus (low model) to 1 (perfect model) [13]. The NSE value criterion is said to be good if the NSE value is more than 0.75; If the NSE value is between 0.36 to 0.75 then the model meets, and if the NSE value is less than 0.36 then the model does not meet [14].

| Station     | Area     | Thiesen coefficient |
|-------------|----------|---------------------|
| Bayongbong  | 295,885  | 0.203               |
| Cikajang    | 129,567  | 0.089               |
| Jatigede    | 343,766  | 0.236               |
| Leuwingitiis| 688,046  | 0.472               |
| Amount      | 1,457,263| 1                   |

Source: Analysis result
3. Results and Discussion

3.1. Secondary Data Analysis

The daily rainfall data from the four rain stations are calculated as the average rainfall of the regions using the polygon Thiessen method. The weight Thiessen at each rainfall station can be seen in table 1.

Spatial data in this study were used to obtain the delineation of the catchment area of the study location, topography, and rivers. Delineation of catchment area is obtained by watershed boundaries and sub-catchment division to be simulated. From the area of each sub-catchment, it will be used to calculate the Curve Number (CN), Initial abstraction, lagtime, canopy, surface, and impervious. The resulted topographic map will be used for the calculation of the Jatigede Reservoir rating curve. The value of curve number of each sub-catchment is obtained from the map overlay of land use, map of soil type, and boundaries of each sub-catchment using GIS tools.

The calculation of the rating curve of Jatigede Reservoir is based on the data planning data that has been done by the Jatigede Reservoir development planner. Data obtained from the planning that has been made include data on the effective width of the Jatigede Reservoir spillway and the maximum discharge that exits in the spillway when the four doors are open. In addition, the curved graph of the planned reservoir capacity can be used as an elevation reference used for rating curve calculation. The rating curve calculation can be carried out using the formula (1).

\[ Q = C \times L \times H^{3/2} \] (1)

where, \( Q \) is the discharge that passes through the overflow (\( m^3/s \)); \( C \) is the coefficient of runoff, \( L \) is the effective width (\( m \)) and \( H \) is the water pressure height above the lighthouse weir (\( m \))
The calculation of Curve Number can be carried out using formula (2) [15].

\[
CN_{\text{composite}} = \frac{A_1CN_A + A_{i+1}CN_{i+1} + \ldots + A_nCN_n}{\sum_{i=1}^{n} A_i}
\]  

(2)

where, \( A \) is the area of each type of land use (\( km^2 \)) and \( CN \) is the curve number coefficient based on soil type and land use.

From the results the CN value is then used to calculate the initial abstraction of each sub-catchment. Initial abstraction is calculated using the following formula [15]

\[
I_a = 0.2S
\]  

(3)

where, \( I_a \) is the initial loss of abstraction and \( S \) is the maximum storage capability.

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

(4)

where, \( S \) is Parameter retention and \( CN \) is the curve number.

Daily climatology data are used to calculate the daily evapotranspiration value of Cimanuk Hulu watershed. In this study, Penman Modification method is used to calculate the value of evapotranspiration using formula (5) as follows:

\[
Etp = c \times \{W \times Rn + (1 - W) \times f(u) \times (ea - ed)\}
\]  

(5)

where, \( Etp \) is evapotranspiration (mm), \( c \) is a condition adjustment factor due to weather at days and nights, \( W \) is a factor that affects the solar radiation, \( f(u) \) is a function of wind speed in comparison, \( Rn \) is the radiation in the ratio of evaporation or solar radiation net (mm/day), \( ed \) is the real vapor pressure (mbar), and \( ea \) is a saturated vapor pressure (mbar).

Cimanuk River profile is used for lagtime calculation and river routing data in modeling using HEC-HMS. Calculation of the lagtime of each sub-catchment uses the following formula (7) [16]

\[
Tc = \frac{L_0 \beta (S+1)^{0.7}}{1140y^{0.5}}
\]  

(6)

\[
Tlag = 0.6 Tc
\]  

(7)

Figure 5. Curve capacity of the reservoirs

Source: BBWS Cimanuk-Cisanggarung
where, $T_c$ is the concentration time (hours), $L$ is the length of the main river (ft), $S$ is the maximum retention $\left(S = \frac{1000}{CN} - 10\right)$, $y$ is the slope ($\%$), and $T_{lag}$ is the time difference between the center of mass of excess rainfall and peak of the hydrograph unit (hours).

### 3.2. Calibration

The results of the running model before calibration produce an NSE value of $-3,868$. To produce the optimum NSE, a trial error is carried out on the constituent parameters of the watershed. This study uses baseflow parameter with a minimum discharge value recorded during the simulation period. The resulting model discharge is far above the observed discharge, then a trial error is carried out on the baseflow to obtain an NSE value of $-2,665$. With NSE $-2,665$ the model discharge still exceeds the observation discharge, so it needs to increase the water loss in the watershed. By conducting a trial error on the initial abstraction value, it can produce NSE value $-2,642$. Then, the trial error of CN is up to the NSE value of $-0,337$. Trial error of manning coefficient results in NSE of $-0,309$. Trial error of max storage is up to the NSE value to $0,100$. Trial error against the max surface of the NSE value becomes $0,376$. Trial error against impervious becomes $0,440$ and the last trial error of lagtime parameters gets NSE value of $0,640$ with RMSE $30,3$. With an NSE value of $0,640$ the model that has been prepared is reliable enough to present the Cimanuk Hulu Watershed.

**Figure 6.** The relationship between precipitation data, discharge observation and discharge model. 
*Source: Analysis result*

Based on the graph of simulation results using HEC-HMS, the model discharge can approach the observation discharge trend, but only a few moments can the model follow the peak and low discharge. The model tends to follow the rainfall data trend because the model simulates the watershed based on the characteristics of watershed without any addition and taking of water in the watershed. Therefore, the observation discharge that shows high discharge during the rainfall is moderate and the discharge which is reduced during the rainfall does not occur due to the addition and taking of water occurring in the watershed.

### 3.3. Model validation

The model validation period is carried out using data in the years of 2016, 2017, and 2018. The parameter value of the watershed characteristic uses the optimum parameter value of the calibration period results. From the validation result to the model, it is obtained the value of Nash and RMSE as presented in table 2.
Table 2. Validation results table

| Years  | Nash  | RMSE |
|--------|-------|------|
| 2016   | -0.104| 65.9 |
| 2017   | 0.472 | 40.4 |
| 2018   | 0.576 | 35.3 |

Source: Analysis result

Based on the results of the validation of the model, the year of 2018 has the best result with Nash value approaching one (1) and the RMSE value approaching 0.

![Figure 7](image)

Figure 7. The relationship between rainfall, observation discharge and model discharge in 2018
Source: Analysis result

3.4. Results modeling before and after the operation of Jatigede Reservoir

3.4.1. Before the operation of the reservoir

Before the operation of the Jatigede reservoir, water flowing from the upstream will flow naturally towards the downstream. It can be seen from the inflow and outflow graphs presented in Figure 8, showing that inflow and outflow are equally. Thus, the surface water cannot be utilized maximally. When abundant water flows and is wasted to the sea, it can even cause flood, otherwise, a shortage of water will be experienced during the dry months (seasons). Therefore, there is a need for management of the use of surface water, one of which is the existence of reservoir. Reservoirs can hold surface water when water surplus occurs and can be utilized during water deficit.

![Figure 8](image)

Figure 8. The relationship between Inflow and Outflow before the operation of the reservoir
Source: Research result
3.4.2. After the operation of the reservoir reservoir

Jatigede Reservoir is a multifunctional reservoir for flood control, raw water supply, irrigation, and hydropower. Jatigede Reservoir has three outlets and a spillway with four-door radial type operations. The spillway is in the body of the right bank of the cliff with a light elevation of + 247 m. Irrigation outlets are in the overflow body with inlet elevation of + 221 m. Diversion tunnel as a raw water outlet is under the spillway with inlet elevation of + 164 M. The last hydropower inlet apron is at elevation of + 221 m to the right of the weir pile and hydropower outlet is downstream of the Jatigede Reservoir.

Simulation of the operation of Jatigede reservoir using HEC-HMS was carried out using the outflow structure method with an initial condition of spillway elevation (+247 m). Reservoir operation simulation using HEC-HMS by adding outlets for water use in accordance with reservoir functions cannot be done optimally. Intake of water using an outlet cannot be controlled. Water in the reservoir will continue to flow through the lowest outlet. The operation of the door control door can only be done on the spillway. Therefore, to be able to take water in accordance with needs is done by modifying reservoir inflow. Before the water enters the reservoir, the water will be deflected using diversion element assuming the water for collection at the outlet has been taken first. The rest of the diverting water through the diversion will be fed into the reservoir and will overflow through the spillway. Water collection for the needs of each outlet and operation of the spillway door opening are carried out constantly during the simulation period.

Simulation results show the operation of the Jatigede reservoir can reduce peak discharge by 28.87% and can control the surface water of Cimanuk watershed, so that it can be put into good use. Jatigede reservoir can fulfill the raw water need of 3,5 m$^3$/s and hydropower at 59,63 m$^3$/s. From the results of the operation of reservoir for raw water and hydropower, Jatigede reservoir can still fulfill the irrigation need of 8,9 m$^3$/s. Water that has been used to turn turbines in the hydropower plant will be channeled back to Cimanuk river, so that it can be reused as a supply irrigation water at the downstream of Cimanuk watershed with an area of 90.000 ha.

Figure 9. Jatigede Reservoir operating pattern in 2018
Source: Research Results

| Table 3. Changes of peak discharge |
|----------------------------------|
| Elements            | Peak Discharges |
|                     | Before   | After   |
| Junction 12/Jatigede | 456,8 M3/S | 131,9 M3/S |
| Reach 12            | 450,2 M3/S | 131,9 M3/S |

Source: Research Results
Based on the peak discharge value in the condition before the operation of the reservoir, it is obtained a value of 450.2 m$^3$/s in the downstream of Jatigede Reservoir. On the other hand, after the operation of the reservoir, the value has dropped to 131.9 m$^3$/s. Therefore, Jatigede Reservoir can reduce flood discharge by storing water in the reservoir.

3.5. Conclusion

Based on research that has been done, it can be concluded that the results of the Cimanuk Hulu watershed calibration produce an NSE value of 0.640 and RMSE value of 30.3. With the results of the NSE model, it is quite reliable in presenting the condition of Cimanuk Hulu watershed. Meanwhile, the best validation result is in 2018 with NSE value of 0.576 with the peak discharge value before the operation of the reservoir is of 456.8 m$^3$/s, and after the operation of the reservoir becomes 131.9 m$^3$/s. The availability of surface water in the Cimanuk watershed can be utilized properly after the operation of Jatigede Reservoir. This can be seen from the results of the operation of the reservoir which can fulfill the needs of raw water and hydropower in accordance with the purpose of dam development. Besides, Jatigede Reservoir can still provide irrigation water of 8.9 m$^3$/s.

Reference

[1] Sukardi S, Warsito B and Kisworo H 2013 Pengelolaan Sungai di Indonesia
[2] Anonim 2010 Pengelolaan sumber daya air wilayah sungai Cimanuk Cisanggarung
[3] Santosa R A B 2003 Kajian Penentuan Urutan Prioritas Penanganan Lahan Kritis Studi Kasus Sub Sub DAS Cimanuk Hulu (Bandung: Institut Teknologi Bandung)
[4] Sulaksana N, Sukiyah E, Sjafrudin A and Haryanto E. 2013 Karakteristik Geomorfologi DAS Cimanuk bagian hulu dan Implikasinyanya terhadap Intensitas Erosi Serta Pendangkalan Waduk Jatigede (Bandung: Bionatura J. Ilmu-ilmu Hayati dan Fis.
[5] Savitri E and Pramono I B 2017 Analisis Banjir Cimanuk Hulu 2016 J. Penelit. Pengelolaan Drh. Aliran Sungai 1 97–110
[6] Pradwipa D P, Jayadi R and Istiarto 2015 Kajian Pemanfaatan Sumberdaya Air Waduk Serbaguna Jatigede, Jawa Barat
[7] Munajad R and Suprayogi S 2012 Kajian Hujan–Aliran Menggunakan Model HEC–HMS Di Sub Daerah Aliran Sungai Wuryantorono Wonogiri, Jawa Tengah J. Geogr. 2 150–7
[8] Harsoyo B 2010 Review Modeling Hidrologi Das Di Indonesia J. Sains Teknol. Modif. Cuaca 11 41–7
[9] Fakhirudin M, Wibowo H, Ridwansyah I, Daruati D, Setiawan F and Surtrisno N 2013 Karakteristik Fisik DAS Cimanuk Sebagai Dasar Konservasi Waduk Jatigede Pros. Pemaparan Has. Penelit. Puslit Geoteknologi LIPI 353–63
[10] Anonim 2015 Hydrologic Modeling System HEC-HMS Applications Guide
[11] Prayudi M, Handayani Y L and Sujatmoko B 2017 Analisis Sensitivitas Parameter Kalibrasi dalam HEC-HMS Jom FTEKNIK 4
[12] Indarto, Adriyani I and Novita E 2008 Kalibrasi Model IHACRES pada Dua DAS Identik Din. Tek. SIPIL 8 89–100
[13] Allen R V, Rusnam, Arlius F and Herdianto R 2019 Analisis Perubahan Penggunaan Lahan Daerah Aliran Sungai (DAS) Air Dingin dan Dampaknya Terhadap Aliran Permukaan J. Tek. Pertan. Lampung 8 153–233
[14] Liew M W Van and Garbrecht J 2003 Hydrologic Simulation of the Little Washita River Experimental Watershed Using SWAT J. Am. Water Resour. Assoc. 413–26
[15] Feldman A D 2000 Hydrologic Modeling System HEC-HMS Technical Reference Manual Hydrogeol. J. Hydrol. Model. Syst. Tech. Ref. Man.
[16] Anonim 2010 Time of Concentration National Engineering Handbook pp 1–15