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FLOOD HYDROGRAPH ANALYSIS USING SYNTHETIC UNIT HYDROGRAPH, HEC-HMS, AND HEC-RAS 2D UNSTEADY FLOW PRECIPITATION ON-GRID MODEL FOR DISASTER RISK MITIGATION

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ABSTRACT: This study presents a flood hydrograph numerical modeling of the Keser watershed for disaster risk mitigation and water resources management for an emergency action plan (EAP) on the Tugu dam. Several formulations for calculating peak discharge, which are associated with information on flood design in Indonesia are regulated in SNI 2415:2016 regarding the procedure of flood discharge calculation and design. This information is important and related to water structure dimensions, risk, costs, and reliability. The complexity of watershed conditions affects the hydrograph shape and volume. Hence, a performance analysis is needed to identify the best current hydrograph model. In this study, the performance of Nakayasu, Gamma 1, and Snyder SUH was analyzed and compared with the numerical modeling using the HEC-RAS 2D hydrodynamics precipitation on grid and HEC-HMS numerical model in the Keser watershed with one-hour rainfall height of 114.92 mm (R50). Based on the calculation results, the hydrologic numerical model flood discharge calculation using HEC-HMS method was 451.1 m^3/s. The peak discharge values obtained using the Nakayasu, Gamma, and Snyder methods were 424.2, 410.4, and 439.4 m^3/s, respectively. The results of the numerical model with HEC-RAS 2D v6.3 with uniform precipitation on the grid obtained a peak discharge hydrograph value of 420.98 m^3/s. Therefore, the highest peak discharge results were obtained from the HEC-HMS method among the three SUH formulas and HEC-RAS calculations. Hence, the deviation of peak discharge value using three SUH, HEC-HMS, and HEC-RAS was obtained under 10%.

Keywords: Flood hydrograph, Synthetic unit hydrograph, Nakayasu, Snyder, Gamma 1, Hec-Ras v6.3

1. INTRODUCTION

Water resources engineering, design, and management in Indonesia, which are related to hydrology analysis still face challenges in mitigating disaster risk. One of the main problems in the analysis is obtaining a peak discharge approach caused by rainfall. Furthermore, rainfall or precipitation in a watershed can turn into a river flow. This shows that there is a connection between precipitation and flow discharge, which is dependent on the watershed's parameters [1]. The evaluations of rainfall-runoff analysis and peak discharge approach contribute to the decision-making and planning of sustainable water resources management strategies in Indonesia.

The problem of this analysis model associated with determining peak discharge in a hydrograph is the unavailability of measured data in several watersheds. Therefore, the calculation approach has been developed with a Synthetic Unit Hydrograph (SUH) using measured characteristics for usage in areas that are unmeasured [2]. Several SUH were developed with important parameters including watershed characteristics, such as shape, size, slope, soil properties, as well as rainfall parameters, namely pattern, intensity, and duration. The synthetic unit hydrograph method is widely used in Indonesia to estimate design floods. Furthermore, it is simple, easy to implement, does not require complex data, and provides relatively good results [1].

Several synthetic unit hydrograph study models have been developed after the first theory by Sherman [3]. The SUH concepts were designed based on the unit theory using watershed characteristics, such as Snyder [4], Nakayasu [5], Gamma I [6], Limantara [7], and ITB [8]. The dimensionless variant was the SCS (Soil Conversion Service) model [9] developed by the US Department of Agriculture, using several watershed criteria in the USA [10, 11, 12]. Clark SUH (1945) was developed based on the conceptual model used by the US Army Corps of Engineers in the HEC-1 program and HEC-HMS [13]. Nash SUH (1957) was designed using the concept of a cascade of an equal linear reservoir [14].

Previous reports showed that various SUH were developed based on Geomorphological Instantaneous unit hydrograph (GIUH) by [15], and then continued by [16, 17]. Furthermore, they can accommodate the geomorphologic parameters to represent a fractal characteristic of the watershed. [18] designed the unit hydrograph H2U

(Hydrogramme Unitaire Universal) [19, 20], using the equation of gamma distribution, which is similar to the Nash model. These designs are the SUH models developed by considering the fractal characteristic of the watersheds approach, which initiates a study about ITS 2 SUH [21, 22].

This study was carried out in the Keser watershed of Trenggalek, East Java. The Tugu dam was built in its downstream to provide flood control, irrigation, and raw water supply. The rainfall-runoff analysis related to peak discharge in this location can contribute to the discharge evaluation of operational and maintenance activities. The previous study in the Keser watershed on a rainfall-runoff model using GR4J showed a good performance for daily and monthly data [23]. Therefore, this study aims to carry out a peak discharge analysis using several synthetic unit hydrographs to evaluate the flood design evaluation in the Tugu dam. This process is then continued by comparing the SUH analysis results with HEC-RAS 2D 6.3 hydrodynamics model and HEC-HMS to determine its performance.

2. RESEARCH SIGNIFICANCE

The hydrological data recording in Indonesia, especially related to rainfall and water level data, are obtained encounters several limitations. The rainfall and AWLR (Automatic Water Level Recorder) data often experience problems from the damaged equipment, and a manual recording system. Therefore, the accuracy and quality of the data are also questioned. Another problem related to hydrological data is related to the distribution of rainfall. Regarding the distribution of rainfall, the number of rainfall stations is often inadequate in terms of quantity, which affects the accuracy of the rainfall distribution data. Thus, in this study the analysis will be simulated with a numerical model using HEC-RAS 2D unsteady flow v6.3, with meteorological data (precipitation) input, uniform precipitation on grid with Thiessen polygon distribution. The HEC-RAS model will be compared with HEC-HMS and several Synthetic Unit Hydrograph (SUH) to analyze the performance result of HEC-RAS 2D v6.3 model.

3. METHODOLOGY

3.1 Study Area

The Tugu dam is located in the downstream area of the Keser watershed in Trenggalek, East Java-Indonesia, as shown in Figure 1. The major function of the dam is to meet the needs of raw water supply, irrigation, flood control, and micro-hydro power plant. Keser watershed has an area of 43.06 km^2 with effective storage of 9.3 million m^3 which can supply the irrigation area of 1,250 hectares, supply raw water of 12 liters per second, and reduce flood by 42.47 m^3/s. The dam also has the potential to supply a micro-hydro power plant of 0.4 megawatts.

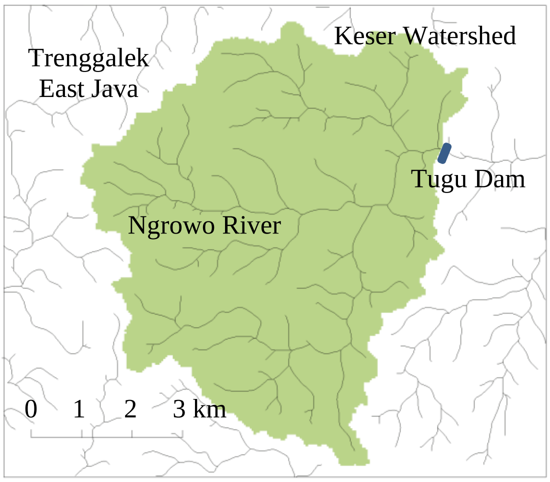

Fig. 1 Keser watershed of Tugu dam in Ngrowo river of Trenggalek-East Java

3.2 Synthetic Unit Hydrograph (SUH)

Water resources management, and flood risk assesment in Indonesia, which are related to hydrology analysis still face challenges in mitigating disaster risk. One of the main problems in the analysis is obtaining a peak discharge approach caused by rainfall. Furthermore, rainfall or precipitation in a watershed can turn into a river flow. This shows between precipitation and flow discharge correlation, affected by characteristics of the watershed [1]. The evaluations of rainfall-runoff analysis and peak discharge approach contribute to the decision-making and planning of sustainable water resources management strategies in Indonesia.

3.2.1 Nakayasu SUH

The Nakayasu synthetic unit hydrograph (SUH) was developed based on several rivers in Japan [24]. Furthermore, its usage in Indonesia began with water resources projects at the Brantas watershed in the 1970s. The parameters in Nakayasu SUH are easily applicable and this method is often used in the planning and management of water resources in Indonesia. The performance Nakayasu SUH has been studied several times and included in the SNI 2415:2016 [25] regarding the procedure of flood discharge calculation and design. The calculation of Nakayasu SUH requires several characteristics of the flow area parameters including time lag (Tg), time of peak (Tp), time base hydrograph (Tb), area of the watershed (A), length of the longest channel (L), and runoff coefficient to calculate the peak discharge (Qp). The Nakayasu hydrograph curve is shown in Figure 2, while the empirical equations of the hydrograph are presented in Table 1.

Table 1 The calculation parameters of Nakayasu SUH

Nakayasu Equations	Parameter
$Q_P = \dfrac{A.\ R_0}{3.6(0.3T_p + T_{0.3})}$	A = Watershed/basin area (km^2) Tp = Time of peak (hour) R_0 = Precipitation/rainfall unit (1 mm) Qp = Peak discharge of Nakayasu SUH (m^3/s)
Tg = 0.4 +0.058L (L>15 km) Tg =$0.21.L^{0.7}$ (L<15 km)	Tg = Lag time (hour) L = length of the longest channel/main stream (km)
Tp = Tg + 0.8 Tr Tr = 0.5 to 1 Tg	Tr= the effective rainfall duration (hour)
$T_{0.3} = \alpha \ .\ tg$	α = watershed form factor α = 2 → Reguler/normal watershed α = 1.5 → The hydrograph with slow rising limb, fast recession limb α = 3 → The hydrograph with fast rising limb, slow recession limb

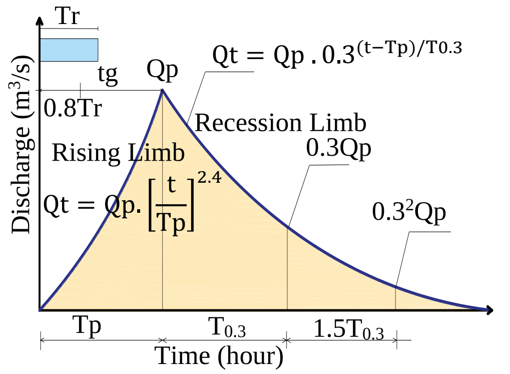

Fig. 2 The Nakayasu SUH curve

The Nakayasu hydrograph method has shown promising performance in predicting the flood hydrograph and estimating the flow rate of water in rivers and streams in Indonesia. However, the accuracy of the method can be affected by various factors, such as the availability and quality of data, the complexity of the river basin, and the rainfall characteristics. Therefore, careful consideration and validation of the method should be conducted before applying it in practical applications.

3.2.2 Gamma 1 SUH

Gamma 1 synthetic unit hydrograph (SUH) was developed by Sri Harto in 1993 [26] based on hydrological behaviors in 30 watersheds on the island of Java. Although this SUH was derived from data in a region, it has a good performance in various parts of Indonesia. It also consists of three main parts of the hydrograph, namely the rising limb, crest, and recession limb. The parameters used in the Gamma 1 SUH comprise several watershed characteristics, the length of the mainstream (L), number of river branches (JN), ratio length of primary streams with that of all streams (Ls), and symmetry factor (SIM), and watershed area in the upstream side of the center of watershed (Au). The empirical equations of the Snyder hydrograph are presented in Table 2, while the curve is shown in Figure 3.

Table 2 The calculation parameters of Gamma 1 SUH

Gamma 1 Equations	Parameter
$Qp = 0.1836.A^{0.5886}.\ Tp^{-0.4008}.\ JN^{-0.2381}$	A = Watershed/basin area (km^2) Tp = Time of peak (hour) JN = Number of river branches Qp= Peak discharge of Gamma 1 SUH (m^3/s)
$Tp= 0.43(\frac{L}{100.SF})^3+1.0665\ SIM+ 1.2775$	L= Length of the longest channe/main river/stream (km) L1= Length of primary streams (km) Ls=Length of all streams (km) SF = Ratio L1/Ls Wl= Watershed wide at 0.25.L (km) Wu= Watershed wide at 0.75.L (km) WF = Wu/Wl Au=Watershed area in the upstream side of the center of watershed (km^2) SIM = Symmetry factor = WF.Au
$Tb= 27.4132.\ Tp^{0.1457}.\ S^{-0.0986S}N^{0.7377}Au^{0.2574}$	Tb = Time of base (hour) S = Slope of river N = Ratio J1/Js J1 = Total number of primary streams Js = Total number of all streams (tertiary, secondary, primary)

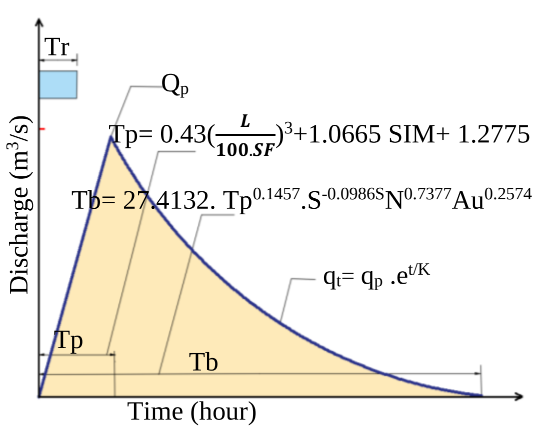

Fig.3 The Gamma 1 SUH curve

3.2.3 Snyder SUH

Snyder SUH was developed in 1938 [27], and it uses unit hydrograph (UH) parametric for analysis of ungauged watersheds in the Appalachian Highlands in the US [28]. Snyder published and provided relationships for estimating UH parameters from watershed characteristics. Furthermore, the parameters used in the SUH include area (A), length of the main river (L), and the length of the main river from the outlet to the centroid of the watershed (Lc), a coefficient derived from gauged watersheds in the area, and represents the effects of retention and storage (Cp) range values between 0.59-0.66, Coefficient derived from gauged watersheds in the same region, and represents variations in watershed slopes and storage characteristics (Ct). The empirical equations of the Snyder hydrograph are presented in Table 3, while the curve is shown in Figure 4.

Table 3 The calculation parameters of Snyder SUH

Snyder Equations	Parameter
$Qp = \frac{0.275.Cp.A}{Tp}$	A = Watershed/basin area (km^2) Tp = Time of peak (hour) Cp= A coefficient derived from gauged watersheds in the area, and represents the effects of retention and storage (0.59-0.66) Qp = Peak discharge of Snyder SUH (m^3/s)
Tp = Ct (L. Lc)^n n = 0.2-0.3	L= The length of the main river/stream (km) Ct= Coefficient derived from gauged watersheds in the same region, and represents variations in watershed slopes and storage characteristics (1-1.2) Lc= The distance from the outlet to a point on the river/stream nearest to the centroid of the watershed area (km)
$t_e = \frac{tp}{5.5}$	t_e=The standard of effective rainfall duration (hour)
t_e> Tr → Tp = tp + 0.25 (Tr-te) t_e< Tr → Tp = tp +0.5 Tr	Tr= The effective rainfall duration (hour)

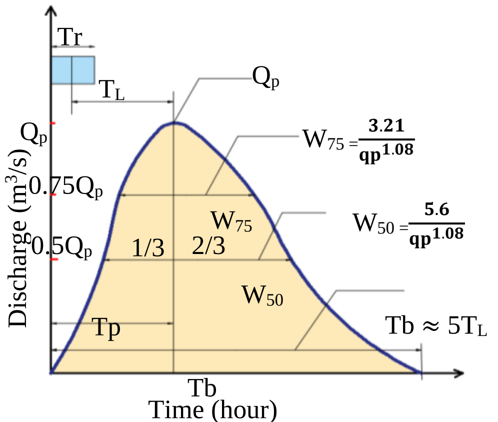

Fig. 4 The Snyder SUH curve

3.3 HEC-RAS 2D Unsteady Flow Hydrodinamics Uniform Precipitation on Grid Model (Precipitation Meteorogical Data)

The flood hydrograph in this study was analyzed using the HEC-RAS v6.3 hydrodynamics model developed by the US Army Corps of Engineering [29]. HEC-RAS (Hydrologic Engineering Centers River Analysis System) is a powerful software tool widely used for modeling and analyzing river systems. HEC-RAS includes a 2D flow module that allows for the simulation of two-dimensional flow in river systems. The 2D flow module can be used to model flow, sediment transport, and water quality in river systems. HEC-RAS 2D v6.3 could conduct a one-dimensional steady flow model and two-dimensional unsteady flow models could improves the performance of several hydraulic structures and lateral buildings, such as weirs, gates, pump stations, bridge scouring, as well as dam break model simulation [30, 31].

HEC-RAS also includes capabilities for simulating precipitation on a grid. The software can import precipitation data in a grid format and then use this data to simulate runoff and flow in the river system. The grid can be defined with a set of X and Y coordinates that define the boundary of the model domain, and the grid cells can be assigned different values of precipitation or other input parameters.

HEC-RAS v6.3 supports input precipitation meteorological data as global boundary conditions input data to simulate real-world conditions in river and stream systems. This type allows users to specify the temporal and spatial distribution of the precipitation data. The data can be entered manually or imported from external sources such as text files or spreadsheets. When the precipitation input data is the point rainfall, HEC-RAS could simulate the rainfall distribution using the polygon Thiessen distribution method. This new feature of meteorological data as a boundary condition in HEC-RAS unsteady flow hydrodynamics model is a valuable tool for simulating real-world conditions in river and stream systems, and can improve the accuracy and realism of hydraulic and hydrologic models.

HEC-RAS 2D flow model carries out an unsteady flow routing model with the diffusion wave equations (DWE) or the shallow water equations (SWE) as default. The SWE uses the original Eulerian-Lagrangian method (SWE-ELM), where the new feature solution can perform shallow water equations that is more momentum-conservative Eulerian method (SWE-EM).

In this study, the Hec-Ras output running model was analyzed with the diffusion wave equations (DWE), which described the conservation of mass and momentum. The general equation used was the mass conservation equation and the momentum conservation equation of Diffusion Wave

Approximation of the SWE in 2-dimensional x and y coordinates. The mass conservation equation is presented below:

$$\frac{\partial H}{\partial t} + \nabla \cdot hV + q = 0 \quad (1)$$

Where t specifies time, V represents velocity vector and q is external contribution (source/sink flux term). H in this case is the water level elevation obtained from:

$$H(x, y, t) = z(x, y) + h(x, y, t) \quad (2)$$

Where z is the bottom of the channel and h specifies the water level. The momentum conservation equation is used as follows:

$$\frac{\partial V}{\partial t} + V \cdot \nabla V = -g\nabla H + \nu_t \nabla^2 V + c_f V + fk \times V \quad (3)$$

Where $\boldsymbol{\nu_t}$ represents the horizontal eddy viscosity, c_f is the coefficient of friction and f is the Coriolis factor. HEC-RAS v6.3 has a sub-grid feature in its computational methods. The volume reservoir of one cell (grid) was determined using the topographic conditions with a denser resolution. The discharge analysis was calculated based on topographic resolution with higher accuracy even though it used a greater roughness computational cell.

3.4 HEC-HMS 4.10 Model

HEC-HMS (Hydrologic Engineering Center's Hydrologic Modeling System) is a hydrologic modeling software developed by the United States Army Corps of Engineers for simulating rainfall-runoff processes. It is used to simulate the hydrologic response of watersheds and to estimate the amount and timing of water that will enter a river channel as a result of precipitation. HEC-HMS is a potent tool for the analysis of direct run-off hydrographs, but it necessitates a solid grasp of the fundamentals of hydrologic modeling as well as a thorough comprehension of the program's capabilities and limitations. It is crucial to use high-quality data and to thoroughly examine and confirm all incoming information and outcomes [13].

The software is based on the concept of the hydrologic cycle, which involves the movement of water through the atmosphere, land, and oceans. The main components of HEC-HMS include: watershed delineation, meteorological data, precipitation analysis and run-off analysis. In this study, the rainfall-runoff calculation to determine flood hydrograph was analyzed with SCS hydrograph method [32], using effective rainfall of 114.92 mm (R_{50}) (first hour rainfall). The distribution of sub-basins area and reach on the Keser watershed is shown in the figure 5.

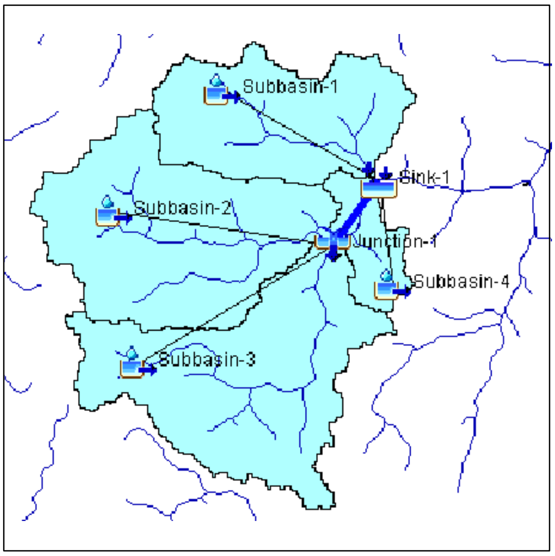

Fig.5 Sub basin distributions and components in HEC-HMS 4.10 model

4. RESULT AND DISCUSSION

The analysis used to determine the peak discharge of the Keser watershed was assessed using three synthetic unit hydrograph (SUH) methods namely Nakayasu, Snyder, and Gamma 1. The SUH calculation results were compared to the numerical model with Hec-Ras 2D hydrodynamic model (6.3 version) and HEC-HMS 4.10. The analysis used rainfall/precipitation data for the first hour of the 50-year return period, which amounted to 114.92 mm. This precipitation value was used as the meteorological input in HEC-HMS 4.10 and HEC-RAS precipitation on grid model, serving as a meteorological boundary condition in HEC-RAS 2D unsteady flow v6.3, where it was set as uniform precipitation on grid model. In HEC-RAS, the point rainfall data was distributed using Thiessen polygons.

Based on the calculation results, the hydrologic numerical model flood discharge calculation using HEC-HMS method was 451.1 m^3/s using SCS hydrograph approach (Fig. 6). The peak discharge values obtained using the Nakayasu, Gamma 1, and Snyder methods were 424.2, 410.4, and 439.4 m3/s, respectively. The results of the numerical model with HEC-RAS 2D v6.3 with uniform precipitation on the grid obtained a peak discharge hydrograph value of 420.98 m3/s. Therefore, the highest peak discharge results were obtained from the HEC-HMS method among the three SUH formulas and HEC-RAS calculations. Hence, the deviation of peak discharge value using three SUH, HEC-HMS, and HEC-RAS was obtained under 10%. The SUH deviation result compared with HEC-HMS were 5.9% for Nakayasu SUH, 9% for Gamma 1 SUH, and 2.6% for Snyder SUH respectively, while the deviation result of HEC-RAS compared with HEC-HMS obtained 6.7%. This shows that their performances are relatively good because the discharge deviation is still below 15%. The result of numerical model 2D flow simulation with HEC-RAS 2D 6.3 are presented in Figure 7. While the recap of the hydrograph curve for the three SUH models, and the numerical models using HEC-HMS 4.10 and HEC-RAS are presented in Figure 8.

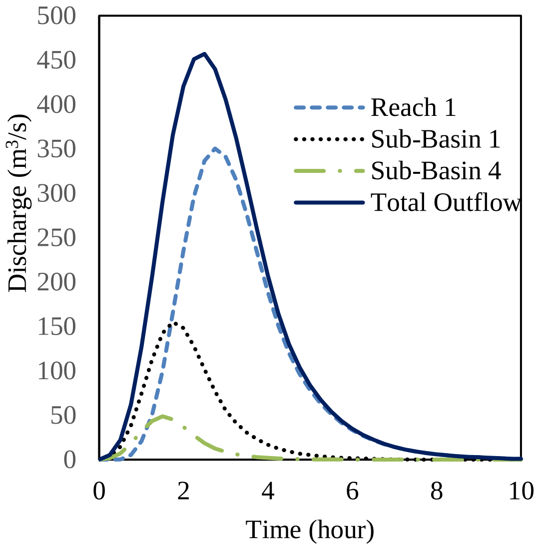

Fig. 6 The flood hydrograph results of HEC-HMS 4.10 numerical model

The comparative diagram of time of peak (Tp) and peak discharge (Qp) for Nakayasu, Snyder, Gamma 1, HEC-HMS and HEC-RAS 2D are presented in Figure 9. The time of peak calculation results obtained relatively large different variability where the HEC-HMS result using lag time of SCS hydrograph obtained a value of 2.15 hours. The values of SUH Nakayasu and Gamma 1 are relatively close with a time peak of 1.79 hours and 1.89 hours, respectively. Meanwhile, a value of 1.183 hour was obtained for the HEC-RAS model in this study. The peak time value of SUH Snyder was 3.5 hours, and it was the furthest from the model calculation.

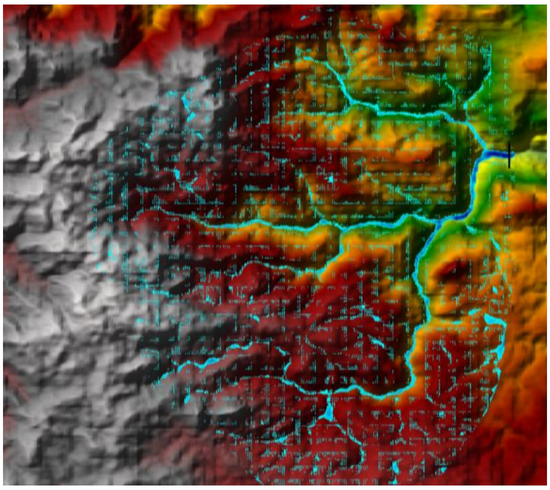

Fig. 7 The 2D flow simulation numerical model result of Hec-Ras 2D v6.3

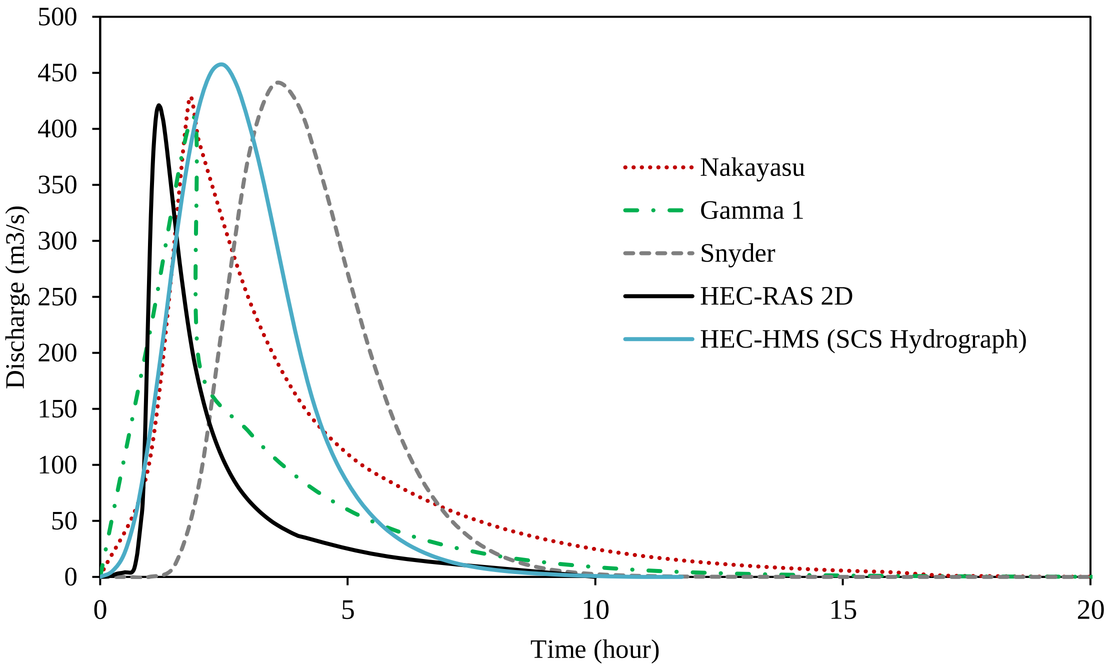

Fig. 8 The flood hydrograph comparison related to peak discharge values of the SUH, HEC-RAS 2D precipitation on-grid, and HEC-HMS.

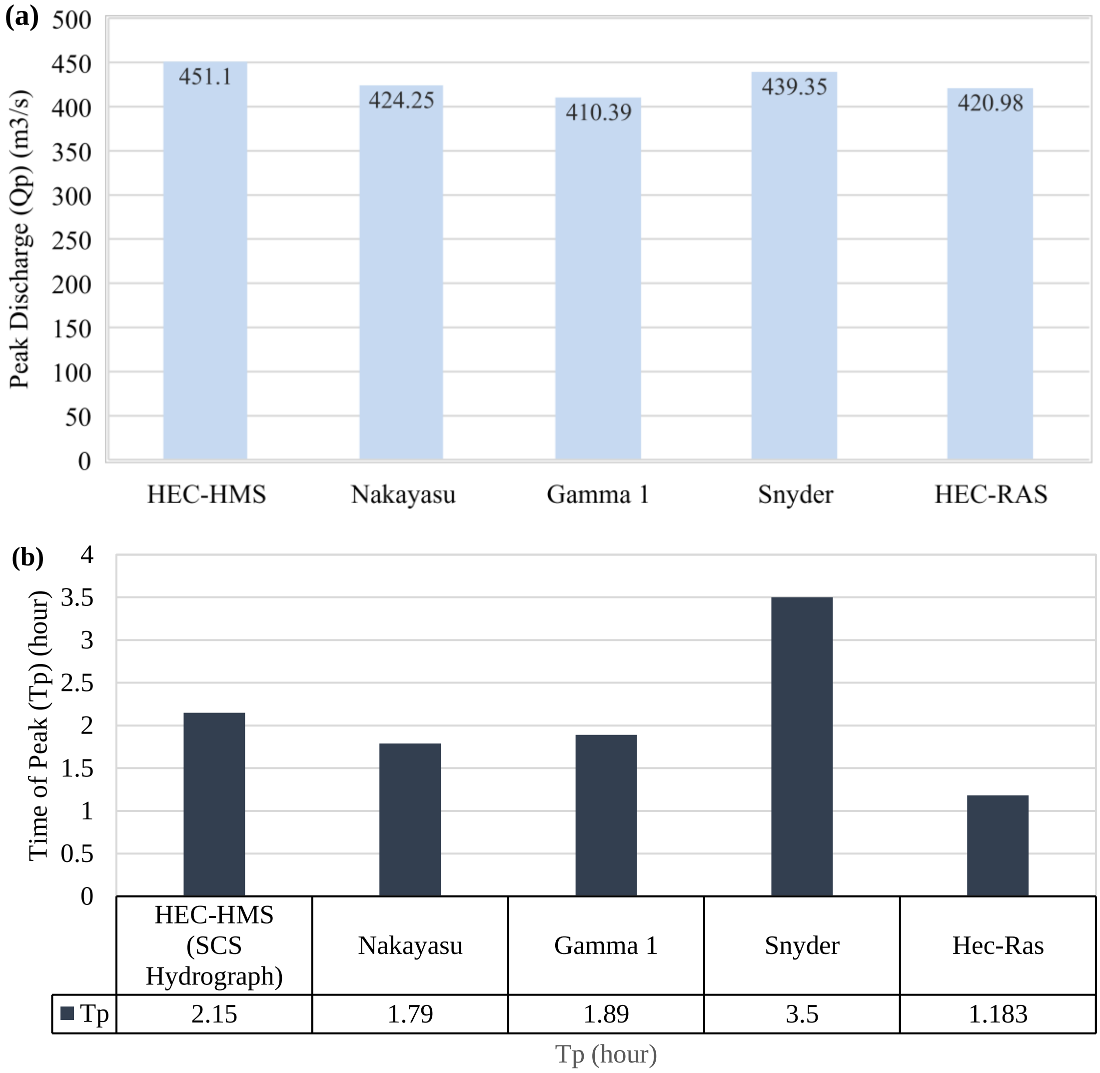

Fig.9 The comparison of Qp (a) and Tp (b) values between the SUH and numerical models

5. CONCLUSIONS

Based on the results performance of the three models of Snyder, Nakayasu, Gamma 1 SUH, HEC-HMS 4.10 and HEC-RAS 2D v6.3 precipitation on grid analysis, the following conclusions were obtained,

1. The peak discharge results obtained good performances between the three SUH models, which was compared with HEC-HMS 4.10 and HEC-RAS 2D v6.3 precipitation on grid numerical model in the Tugu dam location (downstram area of Keser Watershed). The calculations of peak discharge (Qp) using Snyder, Nakayasu, and Gamma 1 obtained values of 424.25 m^3/s, 410.39 m^3/s, and 439.35 m^3/s, respectively. Thus, the numerical model result with HEC-RAS 2D unsteadyflow model using meteorological precipitation data input (uniform precipitation on grid model) showed a peak discharge of 420.98 m^3/s, and the HEC-HMS hydrologic numerical model obtained 451.10 m^3/s.
2. The peak discharge deviation of SUH models and the HEC-RAS 2D flow precipitation on grid numerical model compared with HEC-HMS (SCS hydrograph) were quite close under 10%. Hence HEC-RAS 2D unsteady flow precipitation on grid (meteorological precipitation data) could be an alternative numerical model to determine flood hydrograph.
3. The time of peak (Tp) calculation results showed a relatively large different variability. Tthe HEC-HMS result using lag time of SCS hydrograph obtained a value of 2.15 hours. The values of SUH Nakayasu and Gamma 1 are

relatively close with a time peak of 1.79 hours and 1.89 hours, respectively. Meanwhile, a value of 1.183 hour was obtained for the HEC-RAS model in this study. The peak time value of SUH Snyder was 3.5 hours, and it was the furthest from the model calculation.

The three synthetic unit hydrograph (SUH) peak discharge analysis using Snyder, Nakayasu, and Gamma 1, as well as HEC-HMS 4.10 and HEC-RAS 2D v6.3 numerical modeling using precipitation meteorological input, can be an alternative models for the disaster risk mitigation approach in Tugu Dam and Keser Watershed. Meanwhile, the research-related time of peak analysis needs to be developed further to obtain better analysis results in Indonesia.

6. ACKNOWLEDGMENTS

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