Comparison of Flood Hydrograph of Manikin Dam Watershed Using Synthetic Unit Hydrograph Method, HEC-HMS and Rain on Grid Model with HEC-RAS 2D

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Submitted : 03 December 2024
Revised : 31 January 2025
Accepted : 18 February 2025

Abstract

Manikin watershed is located in Kuaklalo Village which borders Bokong Village, Taebenu Subdistrict, Kupang Regency, East Nusa Tenggara Province which has an area of 49.31 km^2 with a river length of 8.62 km which has a semi-arid climate with a fairly high annual rainfall of around 1000 - 1500 mm. This study aims to compare the design flood discharge and peak hour with Nakayasu Synthetic Unit Hydrograph (HSS) method, GAMA I, HEC-HMS and rainfall discharge model with HEC_RAS 2D in Manikin Dam watershed. In this study, 6-hour rainfall with a return period of 50 years and 100 years was used. Based on the analysis results, the calculation of the hydrological numerical model flood discharge with the HEC-HMS method with a return period of 50 years and 100 years is 511.90 m³/s and 599.30 m³/s with a peak time at the 4th hour. The peak discharge values obtained using the Nakayasu Synthetic Unit Hydrograph and GAMA I methods with a return period of 50 years and 100 years are 342.11 m³/s, 381.14 m³/s and 406.44 m³/s, 456.13 m³/s, and the peak time obtained at SUH Nakayasu is 3 hours and GAMA I is 4 hours. Numerical model results with HEC-RAS 2D v6.6 with 6 hours of rainfall on the grid obtained peak discharge hydrograph values for the 50-year and 100-year return periods of 494.86 m³/s and 604.88 m³/s, with the peak time at the 5th hour. Therefore, the largest peak discharge and peak time results were obtained from the HEC-HMS method among the three SUH formulas and HEC-RAS calculations.

Keywords

Manikin watershed, flood hydrograph, synthetic unit hydrograph, Nakayasu, GAMA I, HEC-HMS, HEC-RAS v6.6

INTRODUCTION

East Nusa Tenggara is an archipelago province with 1192 islands of which 1150 are uninhabited. There are four major islands in East Nusa Tenggara known as “FLOBAMORA” or Flores, Sumba, Timor and Alor. The climate of this region is generally quite dry due to the geographical location and orientation of the cluster of islands towards the circulation of air masses and wind movements that occur in the area [1].

The dry season only lasts for about four to five months in the province [2]. The average annual rainfall in the region ranges between 1,200 and 1,400 mm [3]. Rainfall that is very heavy and frequent in a short period of time can cause flooding. Raw water supply cannot meet the needs of people in cities and villages because the discharge of water sources decreases dramatically during the long dry season. Building rainwater reservoirs with a large storage capacity through the construction of dams is one way to overcome this problem [4].

A dam is a water structure built to store water. The stored water can then be used for various purposes, such as irrigation, power generation, fisheries, and tourism [4]. As irrigation and hydropower generation, dams also provide significant social and economic benefits to communities. [5]. One of East Nusa Tenggara's dams that is still under construction is Manikin Dam the Manikin Dam watershed covers an area of 49.31 km² and its river length is 8.62 km (Figure 1) It is located in Kuaklalo Village and borders Bokong Village in Taebenu District of Kupang Regency, East Nusa Tenggara Province [6].

The hydrological aspect is one that must be considered when constructing this dam. [4]. The hydrological aspect in question is the calculation of the design flood discharge with a model approach that is carried out appropriately and in accordance with the characteristics of a watershed that will produce a flood discharge that is almost comparable to the actual discharge. [7]. The design flood discharge calculation method used by researchers uses the HEC-HMS and HEC-RAS 2D Synthetic Unit Hydrograph Method (SUH).

The SUH method uses watershed characteristics data to analyze flood discharge. [8]. such as watershed area, watershed length, and watershed slope. The concept of (SUH) is to transform rainfall into stream discharge, which was introduced by Sherman in 1932 [9]. The unit

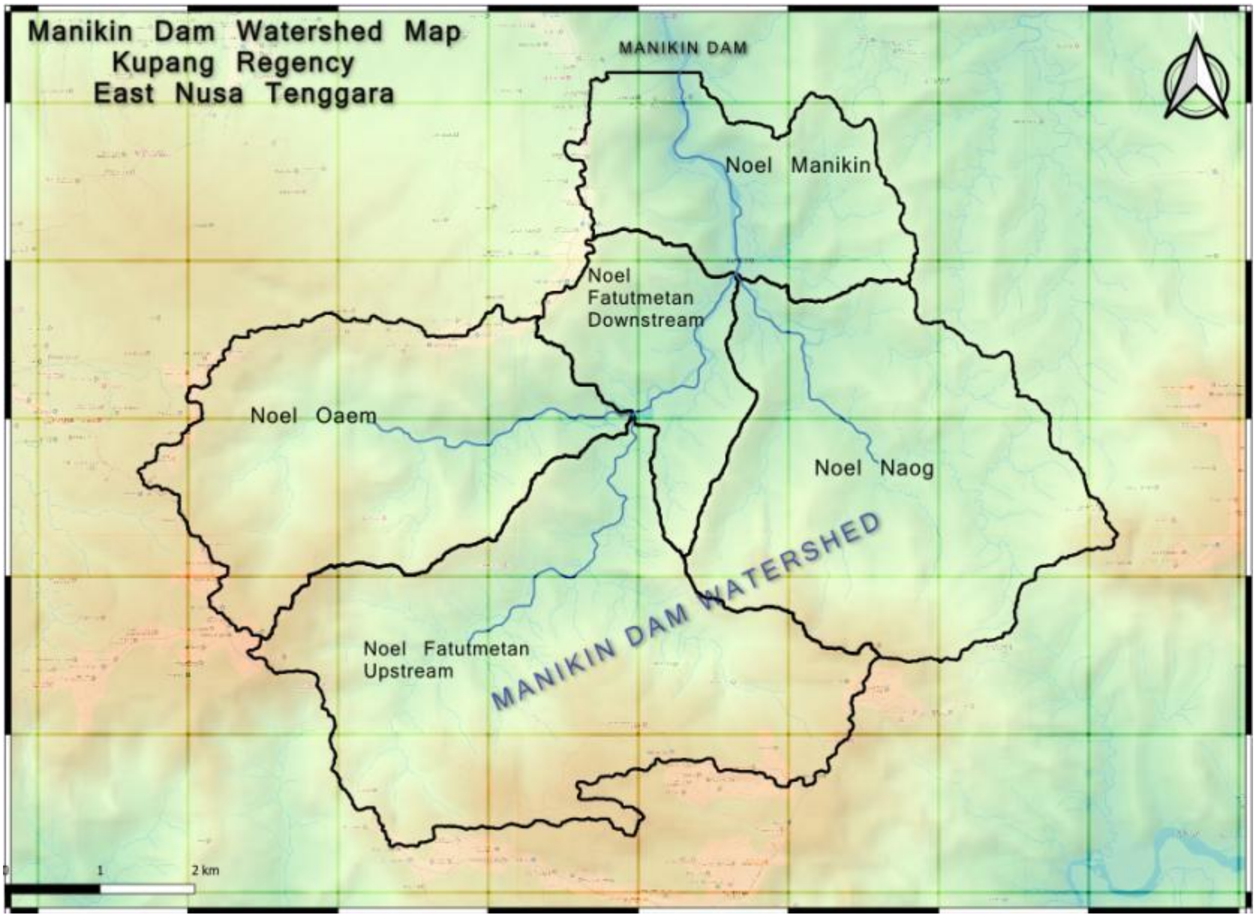


Figure 1 Manikin Dam Watershed

hydrograph superposition calculation requires effective rainfall data that is evenly distributed throughout the watershed for the design flood discharge analysis [10]. The SUH method used to input data is relatively simple and conforms to the law of conservation of mass [11]. The flow hydrograph in a watershed is an important component that is indispensable for planning in the field of water resources, which has a relationship related to the hydrograph and the characteristics of a watershed, the flood hydrograph provides a watershed response to rainfall input. [3], then the calculation of design flood discharge can be used with the Nakayasu Method and HSS Gama. Researchers also used the HEC-HMS (Hydrologic Engineering Center Hydrologic Modeling System) and HEC-RAS (River Analysis System) 2D programs with the Rain on Grid method in calculating the design flood discharge. This research is to find the comparison of flood discharge from HSS, HEC-HMS and HEC-RAS methods.

RESEARCH SIGNIFICANCE

This study focuses on the comparison of flood discharge and peak hours obtained from the HSS, HEC-HMS and HEC-RAS 2D methods, and which method is appropriate to the characteristics of the Manikin Watershed, with the results of this study it can be used as a reference for the manakin discharge that is appropriate to the discharge in field conditions.

METHODOLOGY

A. DATA COLLECTION

The data used is secondary data, including daily rain data around Manikin Watershed, the rain data used is sourced from GSMaP (Global Satelite Mapping of Precipitation) satellite data (https://sharaku.eorc.jaxa.jp/GSMaP/) [12], which is one type of SPPs developed by Japanese scientists, developed by the Japan Science and Technology Agency (JST). However, it is currently developed by the Japan Aerospace Exploration Agency (JAXA). GSMap provides global rainfall data from radiometers at microwave and infrared. This data has a temporal resolution of 1 hour, spatial resolution of 0.1° covering the entire world, which is available from 2000 to the present [13]. Curve Number value data obtained from the processing of land cover data and soil data using Quantum Gis, which includes land cover manikin watershed data from Sentinel 2 satellite data (https://dataspace.copernicus.eu/) [14], while soil data from FAO (Food and Agriculture Organization) (https://daac.ornl.gov/SOILS/guides/Global_Hydrologic_Soil_Group.html) [15], Manikin Watershed location map using DEMNAS data, from the Geospatial Information and Agency (https://tanahair.indonesia.go.id/portal-web/) [16], which is used to determine the area of the das, river length and river slope.

B. SYNTHETIC UNIT HYDROGRAPH (SUH)

The Synthetic Unit Hydrograph method is a method developed in Indonesia, which has been studied using data on river characteristics in Indonesia such as watershed area, watershed length and watershed slope. The concept of the Synthetic Unit Hydrograph method is to transform rainfall into river discharge, which was introduced by Sherman in 1932 [9]. The flow hydrograph in a watershed is the most important thing that is needed for planning in the field of water resources, so in this study it was used to calculate the design flood discharge with the Nakayasu Synthetic Unit Hydrograph Method and the Gama Synthetic Unit Hydrograph.

1. Nakayasu SUH

Nakayasu synthetic unit hydrograph was developed based on several rivers in Japan [17]. The Nakayasu Synthetic Unit Hydrograph, developed by a Japanese national named Nakayasu, is one of the most commonly used hydrograph methods in many water resources planning. It is used primarily to analyze floods in ungauged watersheds. [18]. The use of this method requires several characteristics of the watershed parameters, such as the time lag from the rain surface to the peak of the hydrograph, the time lag from the heavy point of rain to the heavy point of the hydrograph, the hydrograph time lag, the area of the watershed and the length of the longest main river channel, while the empirical equation of thehydrograph are presented in Table 1.

Table 1 The calculation parameters of Nakayasu SUH

Nakayasu Equations	Parameters
$\boldsymbol{Q_p = \frac{A.Ro}{3.6\,(0.3T_p + T_{0.3})}}$	Q_p = Peak discharge of Nakayasu SUH (m³/s) A = Watershed area (km²) Ro = Precipitation/rainfall unit (mm) T_p = Time of peak (hour)
$\boldsymbol{T_p = T_g + 0.8\,T_r}$ $\boldsymbol{T_r = 0.5\ to\ 1\ T_g}$	T_g = Lag time (hour) T_r = the effective rainfall duration (hour)
$\boldsymbol{T_g = 0.4 + 0.058}$ **(L>15 km)** $\boldsymbol{T_g = 0.21.L^{0.7}}$ **(L<15 km)**	L = length of the longest channel/main stream (km)
$\boldsymbol{T_{0.3} = \alpha\ T_g}$	α = 2 (Reguler watershed) α = 1.5 (The hydrograph with slow rising limb, fast recession limb) α = 3 (The hydrograph with fast rising limb, slow recession limb)

2. GAMA SUH

The GAMA I synthetic unit hydrograph was developed by Sri Harto in 1983, this method was developed on the island of Java and is considered suitable for watershed conditions in Indonesia [17]. The parameters needed in the analysis using HSS Gama I such as watershed area (A), the length of the main river channel (L), the length of the river channel to the watershed gravity point (Lc), river slope (S), Drain network density (D), source factor (SF), source frequency (SN), width factor (WF), upstream watershed area (RUA), symmetry factor (SIM), and the number of river encounters (JN), while the empirical equation of thehydrograph are presented in Table 2.

Table 2 The calculation parameters of Gamma I SUH

GAMA I Equations	Parameters
$\boldsymbol{Q_p = 0.1836.A^{0.5886}.Tp^{-0.4008}.JN^{-0.2381}}$	Q_p = Peak discharge of GAMA I SUH (m³/s) A = Watershed area (km²) JN= Number of river encounters T_p = Time of peak (hour)
$\boldsymbol{T_g = 0.4 + 0.058}$ **(L>15 km)** $\boldsymbol{T_g = 0.21.L^{0.7}}$ **(L<15 km)**	L = length of the longest channel/main stream (km)
$\boldsymbol{T_b = 27.4132.Tp^{0.1457}.S^{-0.0986}.SN^{0.7377}.RUA^{0.257}}$	T_b = Time of base (hour) S = Slope of river RUA = Upstream watershed area

3. HEC-HMS Model

A model for transforming rainfall into streamflow, especially for river flow, is the HEC-HMS model. This model is a numerical hydrological model developed by the Hydrologic Engineering Center (HEC) of the United States Army Corps of Engineers. The HEC-HMS program is a computer program for calculating rainfall transformation and conveyance processes in watershed systems. The model can be used for runoff volume, direct runoff, base flow, and channel flow. As described in the book Hydologic Modeling System (HEC-HMS) Technical Reference Manual, the HEC-HMS program is a computer program to calculate the transfer of rainfall and its flow process in a watershed system. In the HEC-HMS software there are calibration and simulation facilities for distribution models, continuous models and the ability to read GIS data [19].

4. HEC-RAS 2D Rain on Grid

The flood hydrograph model in this research was analyzed using the HEC-RAS v6.6 model developed by the United States Army Corps of Engineers. HEC-RAS (Hydrologic Engineering Center River Analysis System) is a widely used software for modeling and analyzing river systems [20]. HEC-RAS has a 2D flow module that enables two-dimensional flow simulation of river systems. [21]
HEC-RAS can also simulate rainfall on the grid. The software can simulate runoff and flow in river systems by importing rainfall data in grid form. A set of X and Y coordinates can be used to define the boundaries of the model domain, and each cell can be assigned a rainfall value or additional parameters. [21] HEC-RAS v6.6 supports rainfall meteorological data input as global boundary condition input data to simulate real-world conditions in river and stream systems. This type allows users to specify the temporal and spatial distribution of rainfall data. Data can be entered manually or imported

from external sources such as text files or spreadsheets. When the input rainfall data is point rainfall, HEC-RAS can simulate the rainfall distribution using the Thiessen polygon distribution method. This new feature of meteorological data as boundary conditions in the HEC-RAS unsteady flow hydrodynamics model is an invaluable tool for simulating real-world conditions in river and stream systems, and can improve the accuracy and realism of hydraulics and hydrology models.

HEC-RAS has the ability to perform two-dimensional unsteady flow routing with the Shallow Water Equation (SWE) or the Diffusion Wave Equation (DWE). The three sets of equations available to HEC-RAS include the Diffusion Wave equation; the original Shallow Water equation (SWE-ELM, which stands for Shallow Water Equation, Eulerian-Lagrangian Method); and a new, more comprehensive Shallow Water equation solution. In addition, SWE has the ability to model the Coriolis effect and turbulence. This study analyzes the running output of the Hec-Ras model using the diffusion wave equation (DWE), which describes the conservation of mass and momentum [20] [21]. The general equations used are the mass and momentum conservation equations of the diffusion wave conservation equation Approximation of the SWE in 2-dimensional x and y coordinates. The mass conservation equation is presented below:

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

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

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

RESULTS AND DISCUSSIONS

The analysis used to determine the peak discharge of Manikin watershed is the synthetic unit hydrograph (SUH) method, namely Nakayasu and Gamma 1.

The results of the SUH calculations were compared to numerical models with the 2D hydrodynamic models Hec-Ras (version 6.6) and HEC-HMS 4.10 (Figure 2).

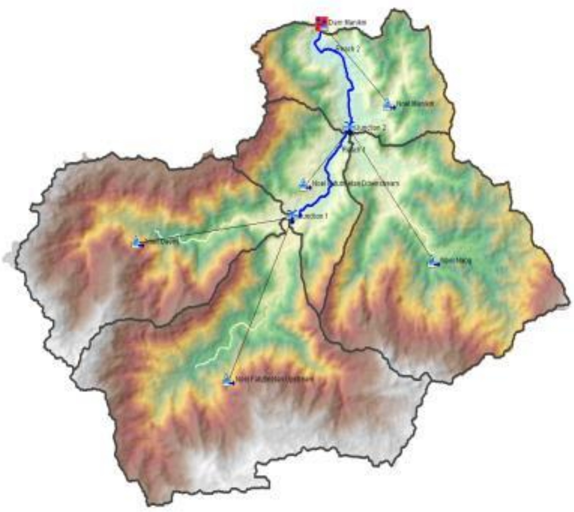


Figure 2 Model HEC-HMS Manikin Watershed

The analysis used 6-hour rainfall data with a return period of 50 years and 100 years. These rainfall values are used as meteorological input in HEC-HMS 4.10 and HEC-RAS rainfall in the 6-hour rainfall model, which serves as meteorological boundary conditions in HEC-RAS 2D unsteady flow v6.6, where the rainfall is set as rainfall in the grid model. Based on the calculation results, the flood discharge of the hydrological numerical model using the HEC-HMS (SCS Curve Number) method with a period of 50 years and 100 years is 511.90 m^3/s and 599.30 m^3/s (Figure 3).

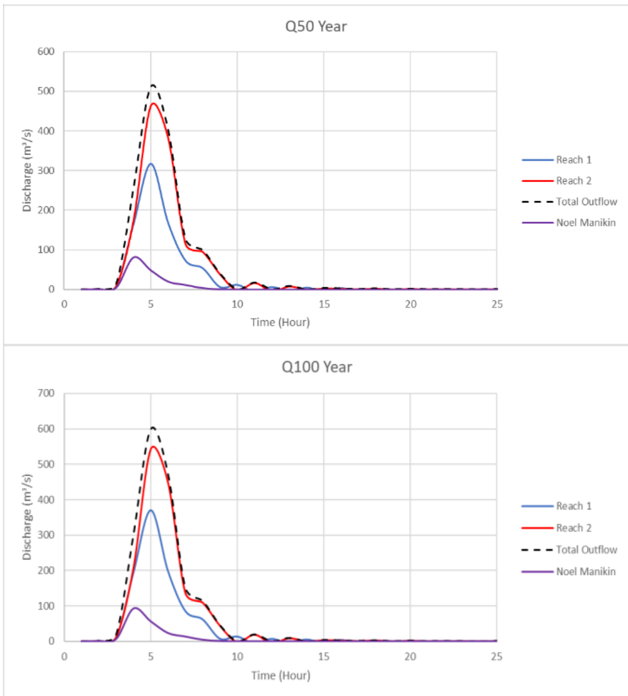


Figure 3 Flood hydrograph result of HEC-HMS

The peak discharge values obtained using the Nakayasu and Gamma 1 methods with a period of 50 years and 100 years are 342.11 m^3/s, 381.14 m^3/s and 406.44 m^3/s, 456.13 m^3/s, respectively. The results of the numerical model with HEC-RAS 2D v6.6 with 6-hour rainfall on a grid with a period of 50 years and 100 years obtained peak discharge hydrograph values of 494.86 m^3/s and 604.88 m^3/s. Therefore, the highest peak discharge results in the 50-year period were obtained from the HEC-HMS (SCS Curve Number) method among the three SUH formulas and HEC-RAS calculations, while for the 100-year period the highest discharge results were obtained from the HEC-RAS method. The flow simulation results of 2D numerical models for 50 years and 100 years periods with HECRAS 2D 6.6 are presented are presented in (Figure 4). While the recap of hydrograph curves for the three SUH models, and numerical models with HEC-HMS 4.10 and HEC-RAS are presented in (Figure 5). The comparison diagram peak discharge (Qp) for Nakayasu, Gamma 1, HEC-HMS and HEC-RAS 2D models is presented in (Figure 6).

Calculation of the peak time of HSS, HEC-HMS (SCS Curve Number) and HEC-RAS 2D methods where the peak time value of SUH Nakayasu is 3 hours, while the HEC-HMS method using the lag time parameter of the SCS Hydrograph obtains the same peak time value as SUH GAMA I, which is 4 hours. Meanwhile, for the HEC-RAS 2D model, the peak hour value is 5 hours, so in this study, the peak time value of HEC-RAS 2D is obtained which is the furthest from the three methods (Figure 7).

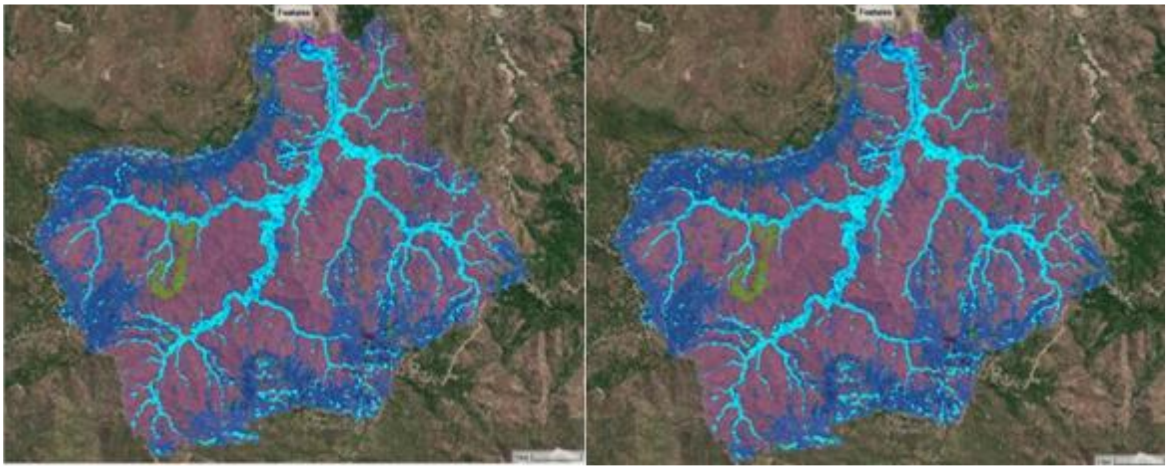


Figure 4 The 2D flow simulation numerical model results of HEC-RAS v6.6 Q50 and Q100

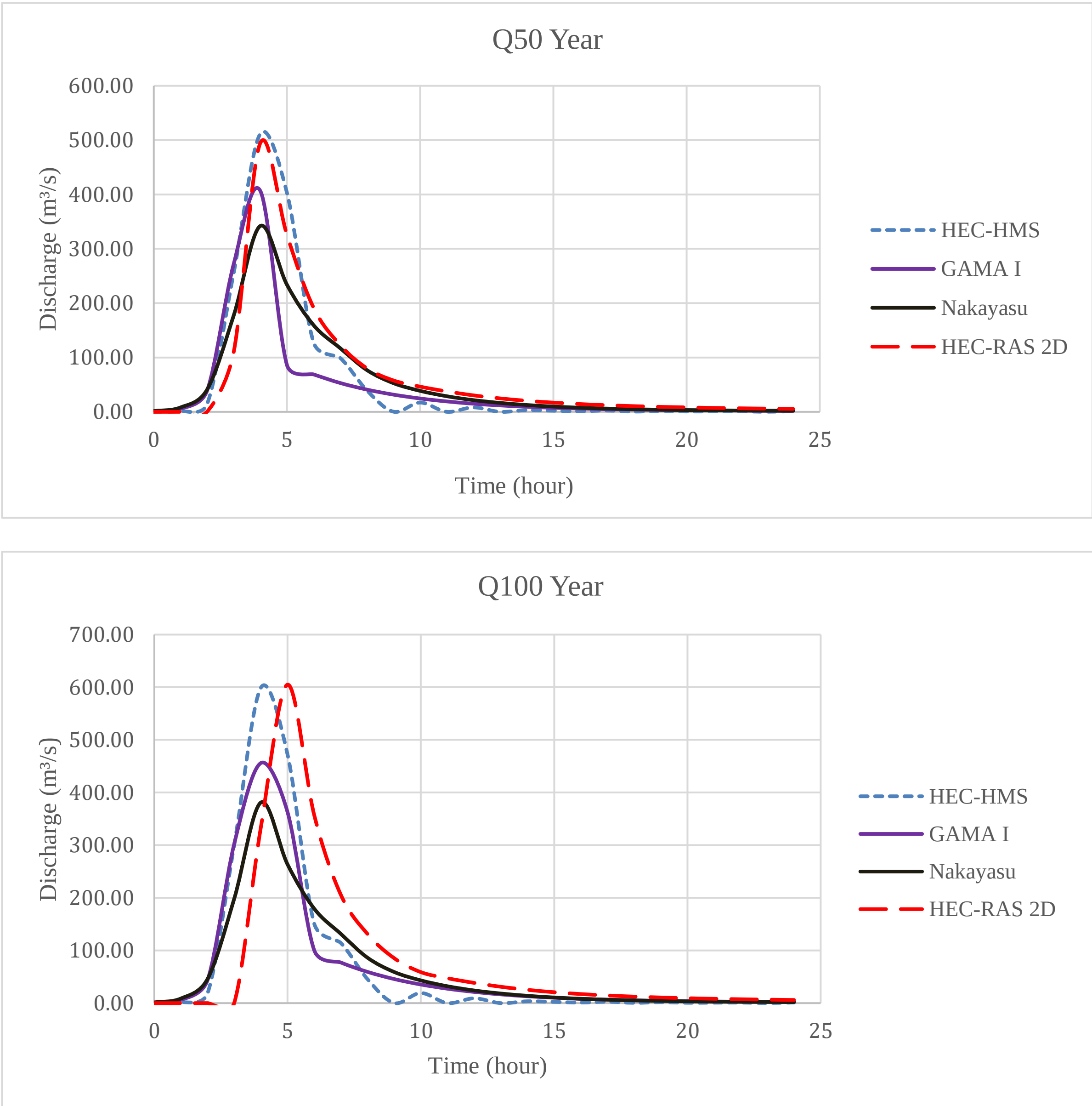
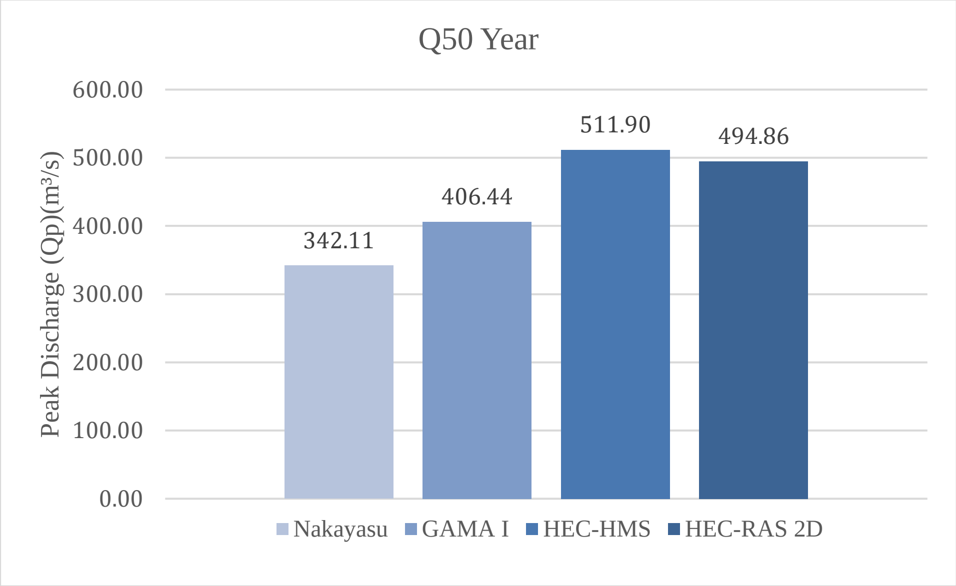


Figure 5 Flood Comparison Chart of SUH Nakayasu, SUH GAMA I, HEC-HMS (SCS Curve Number) and HEC-RAS 2D Methods



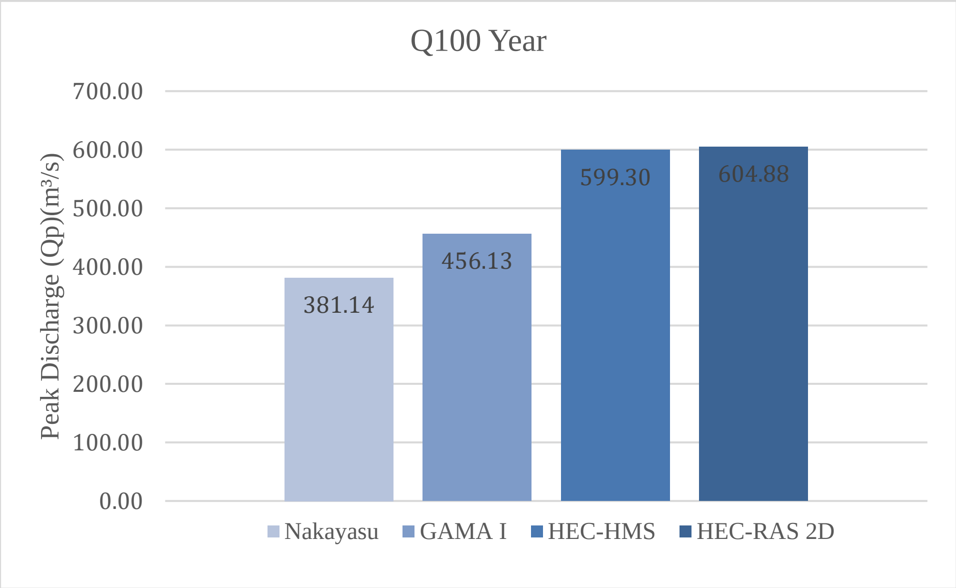


Figure 6 Comparison Diagram of peak discharge of SUH Nakayasu, SUH GAMA I, HEC-HMS (SCS Curve Number) and HEC-RAS 2D Methods

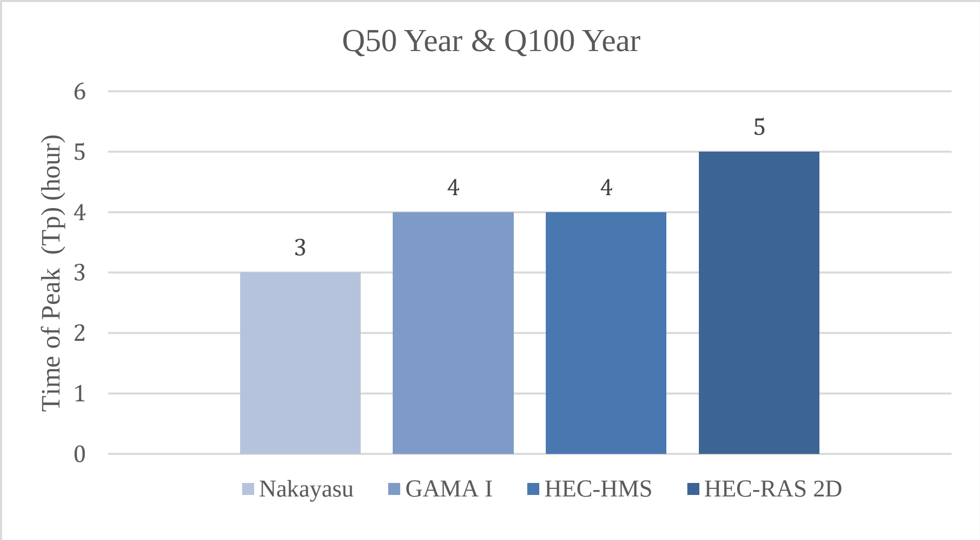


Figure 7 Comparison Diagram of peak time of Nakayasu SUH, GAMA I SUH, HEC-HMS (SCS Curve Number) and HEC-RAS 2D Methods

CONCLUSIONS

From the research results, the peak discharge and peak time of the SUH, HEC-HMS 4.10 and HEC-RAS-2D v6.6 methods were obtained at the Manikin Dam watershed location. Calculation of peak discharge (Qp) with a return period of 50 years and 100 years using the SUH Nakayasu and SUH Gamma I methods obtained sequential values of 342.11 m³/s, 381.14 m³/s and 406.44 m³/s, 456.13 m³/s, with peak times in the SUH Nakayasu method at 3 hours and SUH GAMA I at 4 hours. As for the results of peak discharge and peak time with the HEC-HMS (SCS Curve Number) model with a return period of 50 years and 100 years, the values of 511.90 m³/s and 599.30 m³/s were obtained with a peak time at 4 hours. Meanwhile, the Unsteady Flow HEC-RAS 2D model with the input of rain hours for 6 hours obtained peak discharge with a return period of 50 years and 100 years 494.86 m³/s and 604.88 m³/s with peak time at 5 hours. So it is concluded that the largest peak discharge for the 50-year return period is the HEC-HMS (SCS Curve Number) method and the farthest peak time for the 50-year period is the Unsteady Flow HEC-RAS 2D method, while in the 100-year return period the largest peak discharge and the farthest peak time is the Unsteady Flow HEC-RAS 2D method.

For further research, more synthetic unit hydrograph methods are needed to know the comparison with the methods that have been used so that they are in accordance with the characteristics of the das, besides that longer rainfall data is also needed to get more accurate calculation results.

ACKNOWLEDGMENTS

The authors would like to thank the Global Satellite Mapping of Precepitation (GSMaP) for provided rainfall data in the study area. The author also thanks Copernicus Europe's Eyes on Earth for provided Sentinel 2 data as land cover in the research area, Food and Agriculture Organization (FAO) for providing soil type data in the research area, Geospatial Information Agency (BIG) for providing Digital Elevation Model (DEM) data in in the research area.

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