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Analysis of Designed Flood Discharge Using the Nakayasu HSS Method on the Alo River, Sidoarjo

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ABSTRACT

Design flood discharge is an important parameter in hydrological analysis, used as a basis for planning flood control structures and managing water resources. This study aims to determine the design flood discharge in the Alo Watershed by analysing areal rainfall, design rainfall, effective rainfall, and the Nakayasu Synthetic Unit Hydrograph (HSS). Areal rainfall was calculated using the Thiessen Polygon method based on rainfall data from seven stations: Gedangrowo, Kludan, Putat, Kedungcangkring, Porong, Krembung, and Budugbulus during the 2016–2025 observation period. The design rainfall was analysed using the Log-Pearson Type III Distribution and tested using the Chi-Square and Smirnov-Kolmogorov tests at a significance level of 5%. Furthermore, the design rainfall was converted into a 6-hour hourly rainfall distribution using the Mononobe Method, then calculated as effective rainfall with a runoff coefficient of 0.204. The effective rainfall distribution is used as input to generate flood hydrographs using the Nakayasu Synthetic Unit Hydrograph (HSS) Method. The results of the study indicate that the Log Pearson Type III Distribution passes the distribution suitability test, making it suitable for the analysis of planned rainfall in the Alo Watershed. The Nakayasu HSS analysis shows that the peak flood discharge occurs at the 2nd hour for all return periods and increases with increasing return period. The Design Flood Discharge obtained for return periods of 2, 5, 10, 25, and 50 years is 63.933 m³/s, 72.446 m³/s, 77.339 m³/s, 82.922 m³/s, and 86.742 m³/s, respectively. The results of this study can be used as a basis for planning flood control structures and water resource management in the Alo Watershed.

Contribution to Sustainable Development Goals (SDGs):

SDG 6: Clean Water and Sanitation

SDG 9: Industry, Innovation, and Infrastructure

SDG 11: Sustainable Cities and Communities

SDG 13: Climate Action

SDG 15: Life on Land

1. INTRODUCTION

1.1. Research Background

Flooding is a hydrometeorological disaster that frequently occurs in Indonesia due to high rainfall, land-use changes, and reduced infiltration capacity in river basins (DAS). These conditions cause increased surface runoff, which increases river flow and the

potential for flooding. Land use changes alter watershed hydrological responses by reducing infiltration capacity and increasing surface runoff and peak flood discharge[1]. Therefore, estimating the design flood discharge is necessary as a basis for water resource planning and management, as well as for flood mitigation efforts [Click or tap here to enter text.\[3\]](#).

The design flood discharge is the maximum discharge expected to occur over a specific return period and is generally determined through hydrological analysis using rainfall data and



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watershed characteristics [4][5]. One widely used method for estimating design flood discharge in watersheds without measured discharge data is the Nakayasu Synthetic Unit Hydrograph (HSS) [6]. This method can illustrate the relationship between watershed characteristics and river flow response and is therefore widely used in various hydrological studies and water resource planning in Indonesia [7][8].

Sidoarjo Regency is a flood-prone area due to its low-lying location and its role in the downstream system of the Brantas Watershed. One of the rivers that contributes to the region's drainage system is the Alo River, which connects to the Brantas Delta river network. Its position within the Brantas Watershed drainage system makes it crucial for conveying surface runoff from surrounding catchment areas. Therefore, information on the design flood discharge is essential for water resources planning and flood control measures, as it provides an estimate of the peak discharge that may occur at specific return periods [9]. These hydrological characteristics increase the potential for high river discharge during the rainy season, necessitating design flood discharge analysis as a basis for water resources management and flood mitigation [10].

Although the Alo River plays a strategic role in the drainage system of Sidoarjo Regency, studies specifically addressing design flood discharge analysis in the Alo Watershed remain very limited. In addition, flood events frequently occur across multiple areas of the watershed, particularly in Kalitengah and Ketapang Villages, disrupting community activities and potentially causing socio-economic losses. The limited availability of hydrological information in the Alo Watershed may hinder effective water resources planning and flood mitigation efforts. Therefore, comprehensive hydrological studies are required to provide reliable information on design flood characteristics in this watershed.

Previous studies on design flood estimation using the Nakayasu Synthetic Unit Hydrograph have been conducted widely across various watersheds in Indonesia. However, based on the literature review, no specific study has comprehensively analyzed the design flood discharge characteristics of the Alo Watershed. This indicates a research gap in the availability of hydrological information in the Alo Watershed, particularly for supporting flood mitigation planning and water resources management in Sidoarjo Regency.

The novelty of this study lies in providing one of the first comprehensive analyses of design flood discharge characteristics in the Alo Watershed using the Nakayasu Synthetic Unit Hydrograph method. Although the method employed is widely used in hydrological studies, this research contributes new hydrological information for the Alo Watershed, which has not been extensively investigated previously. The results are expected to serve as a scientific reference for future studies and as supporting information for flood mitigation and water resources management in the study area.

Therefore, this study aims to estimate the design flood discharge of the Alo River using the Nakayasu Synthetic Unit Hydrograph (HSS) method to obtain flood discharge characteristics for various return periods and to provide hydrological information to support flood management in the Alo Watershed [11].

1.2. Literature Review

Flood discharge design analysis is a crucial step in hydrological studies, aiming to describe the magnitude of flow over a specific return period. Flood discharge estimation is influenced by various factors, including watershed characteristics, rainfall, potential rainfall distribution, and the method used to convert rainfall into flow. Therefore, an understanding of the hydrological concepts underlying flood discharge calculations is necessary to obtain representative analysis results.

In this study, flood discharge design analysis was conducted using the Nakayasu Synthetic Unit Hydrograph (HSS) method, which utilizes watershed physical characteristics and rainfall data as the primary parameters. Watershed characteristics, including catchment area, main river length, slope, and land use, play important roles in determining a watershed's hydrological response and the resulting flood hydrograph. Furthermore, rainfall design is determined through areal rainfall analysis and frequency analysis based on annual maximum rainfall data. Therefore, this literature review discusses theories related to watersheds (DAS), rainfall and design rainfall, areal-average rainfall using the Thiessen Polygon method, rainfall frequency analysis, design flood discharge, watershed characteristics affecting flood discharge, and the Nakayasu Synthetic Unit Hydrograph (HSS) method, which serves as the foundation of this research.

1.2.1. River Basin Area (DAS)

A watershed (DAS) is an area bounded by topographic boundaries in the form of ridges that function to capture, store, and channel rainfall toward a single outlet [12]. A watershed is a unified hydrological system that connects the processes of precipitation, infiltration, evapotranspiration, surface runoff, and river flow. Therefore, watershed characteristics are crucial factors in determining an area's hydrological response to rainfall events.

In hydrological studies, identifying watershed boundaries is necessary to determine the extent of the catchment area that contributes to river flow at an outlet. Advances in Geographic Information Systems (GIS) technology enable more accurate watershed delineation through digital analysis of topographic data. One widely used software is QGIS, which can process elevation data to automatically determine watershed boundaries, flow direction, flow accumulation, and river networks. The general elevation data used in hydrological research in Indonesia is the National Digital Elevation Model (DEMNAS) because it has sufficient spatial resolution to depict regional topographic conditions [13].

1.2.2. Rainfall and Design Rainfall

Rainfall is the amount of rainwater that falls on an area over a specific period and is expressed in millimetres (mm). Rainfall is a major component of the hydrological cycle, providing input to surface runoff and river flow. The amount of rainfall in a watershed will affect the volume of water entering the river system.

In hydrological analysis, the commonly used data is annual maximum rainfall, defined as the highest rainfall value in each observation year [14]. This data is then used to derive the design rainfall through statistical analysis [15]. The design rainfall is the amount of rainfall estimated to occur over a specific return period and is used as the basis for calculating the design flood discharge.

Determining the design rainfall is a crucial step because the results will influence the resulting flood discharge.

1.2.3. Areal Average Rainfall (Thiessen Polygon)

In hydrological analysis, rainfall data from rain gauge stations represent only point rainfall conditions at those locations. However, flood discharge calculations require rainfall values that represent the entire watershed area. Therefore, point rainfall data must be converted into areal average rainfall.

One method commonly used to determine areal average rainfall is the Thiessen Polygon Method. This method considers the area of influence of each rainfall station within a watershed[16]. The watershed area is divided into several polygons, each representing the area closest to a particular rainfall station. The boundaries of the polygons are formed by drawing perpendicular bisectors between adjacent rainfall stations[17].

The average areal rainfall is calculated by weighting each station's rainfall by the proportion of the watershed area it represents within its Thiessen polygon. Consequently, stations with larger areas of influence contribute more to the resulting average rainfall. The Thiessen Polygon Method is widely used in hydrological studies because it provides a more representative estimate of watershed rainfall than simple arithmetic averaging, particularly when rainfall stations are unevenly distributed.

The delineation of Thiessen polygons can be performed using Geographic Information System (GIS) software, allowing more accurate determination of the area represented by each rainfall station. The resulting areal-average rainfall is subsequently used as the basis for rainfall frequency analysis and for determining design rainfall.

1.2.4. Rainfall Frequency Analysis

Rainfall frequency analysis is a statistical method used to estimate the probability of an extreme rainfall event based on historical data. The primary objective of frequency analysis is to obtain design rainfall for various return periods, which are used in water structure planning and flood analysis.

Some commonly used probability distributions in hydrological analysis include the Normal, Log-Normal, Gumbel, and Log-Pearson Type III distributions. The Log-Pearson Type III distribution is frequently used in hydrological frequency analysis because of its relatively flexible representation of rainfall data. Each distribution has different characteristics, requiring testing to determine which distribution best fits the analysed rainfall data [18].

Distribution selection is performed using goodness-of-fit tests, such as the Chi-Square and Kolmogorov-Smirnov Tests. Distributions that meet the test criteria are then used in the design rainfall calculations. Among the available probability distributions, Gumbel and Log-Pearson Type III are widely used and widely accepted in hydrological analyses in Indonesia [19], thereby increasing the reliability of the analysis results in describing the hydrological conditions of the study area.

1.2.5. Design Flood Discharge

The design flood discharge is the maximum discharge estimated to occur in a river with a certain probability of occurrence, expressed in terms of a return period[20]. The return period indicates the average time interval over which a hydrological

event of the same magnitude or greater than the analyzed value occurs.

In the field of water resources, the design flood discharge is an important parameter for planning and evaluating hydraulic structures, such as drainage channels, bridges, culverts, embankments, and other flood control structures. Accurately determining the design flood discharge will impact the safety and effectiveness of infrastructure against flood risk. The estimation of design flood discharge generally involves hydrological analyses, including areal rainfall calculation, rainfall frequency analysis, and rainfall-runoff transformation using an appropriate synthetic unit hydrograph method[21].

1.2.6. Watershed Characteristics that Affect Flood Discharge

The watershed's physical characteristics influence the magnitude of flood discharge in a river. One influential parameter is the watershed area. The larger the catchment area, the greater the volume of water that can potentially collect and flow towards the outlet, thus increasing the resulting flood discharge.

The length of the main river also affects the travel time of flow from upstream to downstream. Rivers with longer channels generally have longer times of concentration than shorter rivers. Rivers with longer channels generally have longer periods of concentration than shorter rivers. Furthermore, the slope of the watershed influences the velocity of surface flow. Watersheds with steeper slopes tend to produce faster flow, allowing peak discharge to be reached more quickly.

Another influencing characteristic is land use. Converting vegetative land to built-up areas can reduce soil infiltration and increase surface runoff. Consequently, the volume of flow entering the river increases, potentially increasing flood discharge[22].

These physical characteristics of the watershed can be obtained through spatial analysis in QGIS using DEMNAS data [23]. Through the process of watershed delineation and extraction of morphometric parameters, information on watershed area and main river length is obtained, which are then used in hydrological analysis.

1.2.7. Nakayasu Synthetic Unit Hydrograph (HSS)

The Synthetic Unit Hydrograph (HSS) is a method for estimating flood hydrographs in watersheds lacking continuous observed discharge data. This method was developed based on the empirical relationship between watershed physical characteristics and the river flow response to effective rainfall.

One method widely used in Indonesia is the Nakayasu Synthetic Unit Hydrograph (HSS). This method is based on watershed morphometric parameters, such as watershed area and main river length, making it suitable for use in areas with limited hydrological data. The Nakayasu HSS produces a hydrograph that depicts changes in discharge over time, from rising discharge to peak discharge to declining discharge during the recession limb of the hydrograph [24].

The main parameters used in the Nakayasu HSS method include watershed area (A), main river length (L), time of concentration, peak time (Tp), recession time (T0.3), hydrograph base time, and peak discharge (Qp)[25]. These parameters are used to generate a synthetic flood hydrograph, which is then used in the design flood discharge analysis.

The advantages of the Nakayasu HSS method include its ability to estimate flood discharge in watersheds lacking measured discharge data, its relatively simple data requirements, and its ease of application across various watershed conditions. However, the results' accuracy is strongly influenced by the quality of rainfall data and the accuracy of the watershed characteristic parameters used in the calculations.

The equations used to determine the main parameters of the Nakayasu Synthetic Unit Hydrograph are presented as follows[26]:

For watersheds with a main river length of less than 15 km ($L < 15$ km), the lag time (T_g) is calculated using the following equation:

$$T_g = 0,21 \times L^{0,7}$$

Meanwhile, for watersheds with a main river length greater than or equal to 15 km ($L > 15$ km), the lag time (T_g) is calculated as:

$$T_g = 0.4 + 0.058L$$

The effective rainfall duration (T_r) is generally assumed to range between:

$$T_r = (0,5 \times T_g) \text{ to } T_g$$

The time to peak discharge (T_p) is calculated as:

$$T_p = T_g + (0,8 \times T_r)$$

The recession time ($T_{0,3}$), defined as the time required for the discharge to decrease to 30% of the peak discharge, is calculated as:

$$T_{0,3} = \alpha \times T_g$$

The coefficient α represents the watershed flow characteristic parameter used to determine the shape of the hydrograph's recession limb. In this study, α value of 2 was adopted to represent normal flow conditions within the watershed.

1.3. Research Objective

This study aims to determine the Design Flood Discharge of the Alo River in Sidoarjo Regency using the Nakayasu Synthetic Unit Hydrograph (HSS) method based on analysis of annual maximum rainfall data. The Design Flood Discharge is calculated for return periods of 2, 5, 10, 25, and 50 years.

2. MATERIALS AND METHODS

The research phase began with delineating the Alo River watershed in QGIS using DEMNAS data to obtain the physical characteristics required for hydrological analysis. Based on the delineation results, the watershed area was 60.435 km² and the main river length was 8.351 km, which were then used as parameters for calculating the Nakayasu Synthetic Unit Hydrograph (HSS). Furthermore, regional rainfall calculations were performed using the Thiessen Polygon method based on data from seven rainfall stations that influenced the research watershed [27]. The annual maximum rainfall data used in this study covered 10 years (2016–2025), representing the most complete and consistent dataset available for the study area. In hydrological studies conducted in data-scarce regions, relatively short rainfall records are frequently used to estimate design floods when long-term observations are unavailable [8]. Therefore, the available dataset was considered adequate to provide preliminary estimates of design flood discharge in the Alo Watershed.

The results of the regional rainfall calculations were summarised to obtain annual maximum rainfall data, which were subsequently analysed using frequency analysis methods. Frequency analysis was carried out using several probability distributions, namely the Normal Distribution, Log-Normal Distribution, Gumbel Distribution, and Log-Pearson Type III Distribution [28]. The selection of the most appropriate probability distribution was performed through goodness-of-fit testing using the Chi-Square and Kolmogorov–Smirnov methods to evaluate the suitability of the theoretical distributions for representing the observed rainfall data [29].

Probability distributions that satisfied the goodness-of-fit criteria were used to determine the design rainfall, which subsequently served as input data for the calculation of design flood discharge using the Nakayasu Synthetic Unit Hydrograph (HSS) method. The Nakayasu HSS method is widely applied in watersheds with limited discharge observations because it can estimate flood hydrographs using watershed morphometric characteristics and rainfall data while accounting for temporal discharge variation. The design flood discharge calculations were carried out for return periods of 2, 5, 10, 25, and 50 years [30]. The complete research stages are presented in Figure 1.

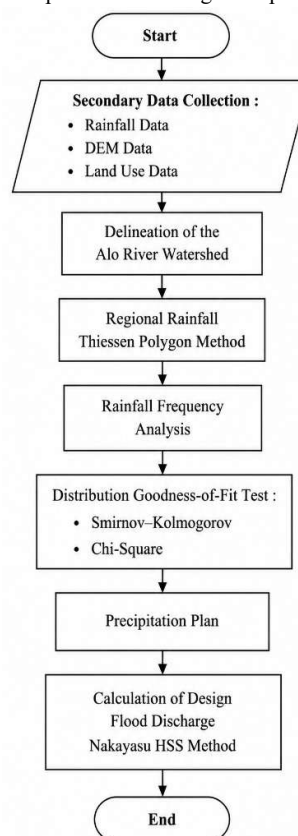


Fig 1. Research Stages of Design Flood Discharge Analysis Using the Nakayasu HSS Method.

3. RESULT AND DISCUSSION

3.1. Watershed Delineation

The results of the Alo River watershed delineation are shown in Figure 2. Based on the delineation, the watershed area is 60.435 km², and the main river length is 8.351 km. The Alo Watershed is characterized by relatively flat topography, which influences

the hydrological response of the watershed. Based on the DEMNAS analysis, the watershed is predominantly lowland, with gentle slopes. Land use within the watershed is dominated by agricultural areas, followed by settlements and plantations. In addition, the dominant soil type in the study area is alluvial soil, which generally has moderate infiltration capacity. However, the expansion of settlement areas may reduce infiltration and increase surface runoff. These watershed characteristics were considered when determining the runoff coefficient for the effective rainfall

analysis. The watershed area and main river length are important parameters in the calculation of the Nakayasu Synthetic Unit Hydrograph (HSS) because they influence the watershed's hydrological response and the characteristics of the resulting flood hydrograph, as shown in Figure 2. These parameters are then used as input data in the calculation of the design flood discharge.

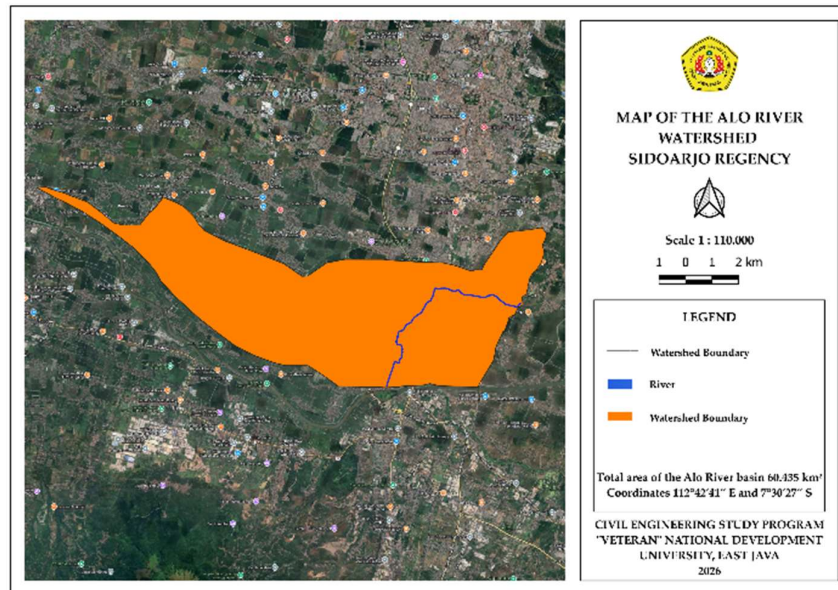


Fig 2. The Results of the Alo River Watershed Delineation.

3.2. Areal Rainfall Analysis

Areal rainfall analysis was conducted using the Thiessen Polygon method to obtain the average rainfall representative of the Alo River Basin (DAS). This analysis used 10 years (2016–2025) of daily maximum rainfall data obtained from seven rainfall stations: Gedangrowo, Kludan, Porong, Budugbulus, Putat, Krembung, and Kedungcangkring. The Thiessen Polygon method

assigns weights to each rainfall station based on its area of influence, allowing for a proportional representation of rainfall distribution across the entire Alo Watershed.

The distribution of the area of influence of each rainfall station based on the Thiessen Polygon method is shown in Figure 3, while the calculated area of influence and Thiessen weights for each rainfall station are presented in Table 1.

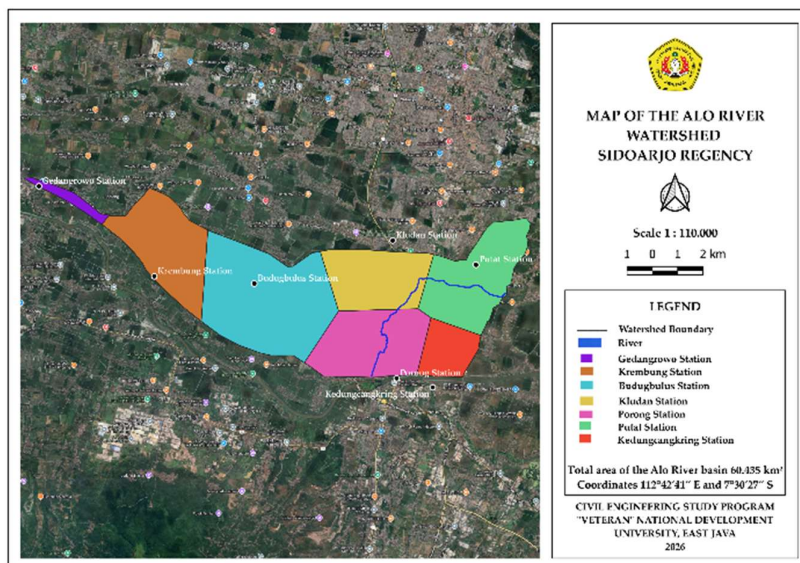


Fig. 3. The Distribution of the Area of Influence of each Rainfall Stations based on the Thiessen Polygon.

Table 1. The Calculated Area of Influence and Thiessen Weights for each Rainfall Stations

Rain Stations	Area of each Rainfall Station	W
	(km ²)	(%)
Gedangrowo	1.071	0.018
Kludan	8.167	0.135
Putat	10.251	0.170
Kedungcangkring	3.718	0.062
Porong	9.853	0.163
Krembung	9.896	0.164
Budugbulus	17.479	0.289
Total	60.435	1

The obtained Thiessen weights were used to calculate annual maximum rainfall (Rmax) as input for the rainfall frequency analysis. The results of the Rmax calculation during the observation period are presented in Table 2.

Table 2. The Results of the Rmax Calculation during the Observation Periods

Years	Rmax
	(mm)
2016	100.037
2017	115.688
2018	81.538
2019	82.340
2020	97.291
2021	85.403
2022	99.312
2023	71.282
2024	80.679
2025	104.675
Total	918.246
n	10
R	91.825

3.3. Design Rainfall Analysis

The design rainfall analysis for the Alo Watershed was conducted using the Type III Log-Pearson distribution based on annual maximum rainfall data (Rmax). The calculation was performed using statistical data parameters, namely the standard deviation (S), skewness coefficient (Cs), kurtosis coefficient (Ck), and variation coefficient (Cv), which were used to determine the frequency factor for each return period to obtain the design rainfall. The results of the design rainfall analysis for return periods of 2, 5, 10, 25, and 50 years are presented in Table 3.

Table 3. The Results of the Design Rainfall Analysis for return Periods of 2, 5, 10, 25, and 50 years

Return Time (year)	Frequency Factor (KT)	Precipitation Plan (XT)
		(mm)
2	-0.00017	90.917
5	0.84157	103.023
10	1.28166	109.982
25	1.75103	117.922
50	2.05429	123.354

The suitability of rainfall data to the Log-Pearson Type III Distribution was tested using the Chi-Square and Smirnov-Kolmogorov tests at the 5% significance level ($\alpha = 0.05$).

For the Chi-Square goodness-of-fit test, the annual maximum rainfall data were grouped into four class intervals. The number of class intervals was determined using Sturges' equation:

$$K = 1 + 3.3 \log n$$

$$K = 1 + 3.3 \log 10$$

$$K = 4$$

The degree of freedom (dk) was calculated using the equation:

$$dk = K - 1 - \alpha$$

$$dk = 4 - 1 - 2$$

$$dk = 1$$

Where (K) is the number of class intervals and (α) is the number of estimated distribution parameters. In this study, the value of (α) was taken as 2 according to the procedure proposed in the Chi-Square goodness-of-fit test [31]. Therefore, based on four class intervals, the degree of freedom used in this study was 1. For the Smirnov-Kolmogorov test, the empirical cumulative distribution function was compared with the theoretical cumulative distribution function from the Log Pearson Type III distribution, and the maximum absolute difference, Δ_{max} , was subsequently determined.

The test results showed that the calculated C^2 value was less than the critical C^2 , and the calculated Δ_{max} value was less than the critical Δ , meeting the acceptance criteria and indicating suitability for use in the design rainfall analysis for the Alo Watershed. The results of the goodness-of-fit tests are presented in Table 4.

Table 4. Chi-Square and Smirnov-Kolmogorov Goodness-of-Fit Test Results

α	Chi Square (C^2 Calculate)	C^2 Critical	Smirnov (Δ_{max})	Δ Critical	Decision
5%	0.4	3.841	0.129	0.41	Accepted

The resulting design rainfall data were then used as input data for the rainfall intensity analysis and design flood discharge calculations in the next stage. results.

3.4. Effective Rainfall Analysis

The runoff coefficient (C) used in this study was determined based on land use characteristics within the Alo Watershed. The coefficient values assigned to each land use category were adopted from a runoff coefficient classification commonly used in hydrological studies [31]. Agricultural land, settlements, plantations, grassland, and undeveloped land predominantly occupy the watershed. The area of each land use category within the Alo River Watershed was determined using GIS analysis in QGIS by superimposing the watershed boundaries over the land use data. Land use composition and the corresponding runoff coefficient values used in this study are presented in Table 5. Based on a weighted-average calculation of land-use characteristics, the composite runoff coefficient for the Alo Watershed was 0.204.

Table 5. Land Use Composition and Runoff Coefficient Values in the Alo Watershed

Land Type	Area (km ²)	C	Area × C
Agricultural	34.446	0.16	5.511
Plantations	8.546	0.15	1.282
Grassland	0.505	0.14	0.071
Settlements	16.629	0.325	5.404
Undeveloped	0.309	0.2	0.062
Total	60.435	0.975	12.330

The effective rainfall analysis in the Alo Watershed was then conducted using the Mononobe Method to convert the design rainfall into a 6-hour hourly rainfall distribution adjusted to the watershed concentration time. The obtained hourly rainfall distribution was subsequently used to calculate the effective rainfall using the composite runoff coefficient. The resulting effective rainfall was then used as input for the design flood hydrograph analysis. The results of the 6-hour hourly rainfall distribution and effective rainfall calculations for each return period are presented in Table 6.

Table 6. Six-Hour Hourly Effective Rainfall Distribution for Different Return Periods

Hour	Hourly Rainfall Distribution (R _t)	Hourly Effective Rainfall (Re,t)				
		(mm/hour)				
		2	5	10	25	50
		(year)	(year)	(year)	(year)	(year)
1	55.032%	10.208	11.567	12.349	13.240	13.850
2	14.304%	2.653	3.007	3.210	3.441	3.600
3	10.034%	1.861	2.109	2.251	2.414	2.525
4	7.988%	1.482	1.679	1.792	1.922	2.010
5	6.746%	1.251	1.418	1.514	1.623	1.698
6	5.896%	1.094	1.239	1.323	1.419	1.484
Total Effective Rain (mm/day)		18.549	21.019	22.439	24.059	25.167

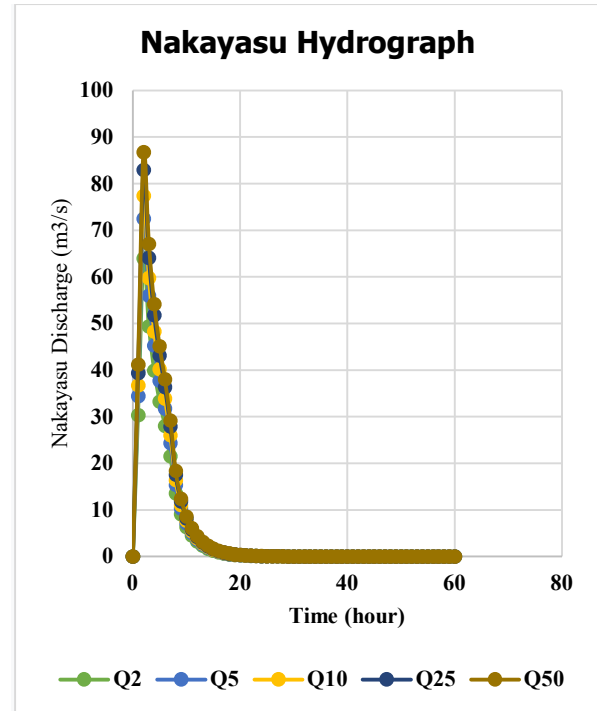
3.5. Hydrological Simulation Results

The design flood discharge analysis for the Alo Watershed was conducted using the Nakayasu Synthetic Unit Hydrograph (HSS) method based on the effective rainfall distribution obtained in the previous step. This method was used to generate the design flood hydrograph by considering watershed hydrological parameters, such as watershed area, main river length, lag time, time to peak discharge, and hydrograph recession time. The values of the Nakayasu HSS parameters used in this study, including lag time (T_g), rainfall duration (T_r), time to peak (T_p), recession time ($T_{0.3}$), and watershed coefficient (α), are presented in Table 7.

Table 7. Calculated Parameters of the Nakayasu Synthetic Unit Hydrograph for the Alo Watershed

Parameter	Value
$T_g = 0,21 \times L^{0,7}$	0.928 hour
$T_r = (0,5 \times T_g) \text{ to } T_g$	0.696 hour
$T_p = T_g + (0,8 \times T_r)$	1.485 hour
$T_{0,3} = \alpha \times T_g$	1.856 hour
α	2

Based on the analysis results, the design flood hydrographs for return periods of 2, 5, 10, 25, and 50 years show a similar pattern, with peak flood discharge occurring in the second hour for all return periods. Increasing the return period results in larger peak discharges because the design rainfall increases. The resulting flood hydrographs are presented in Figure 4, while the peak discharge values for each return period are presented in Table 8.

**Fig. 4.** Nakayasu Synthetic Unit Hydrographs for 2, 5, 10, 25, and 50 Year Return Periods.**Table 8.** Peak Design Flood Discharges for Different Return Periods

No	Return Period (year)	Peak Flood Discharge (m ³ /s)
1	2	63.933
2	5	72.446
3	10	77.339
4	25	82.922
5	50	86.742

The peak discharge for all return periods occurred during the second hour after rainfall onset. This relatively short time to peak indicates that the Alo Watershed responds rapidly to rainfall events. The rapid hydrological response is influenced by the relatively short main river length, predominantly flat topography, and the presence of settlement areas within the watershed, which reduce infiltration and increase surface runoff.

The hydrographs generated using the Nakayasu HSS method show a steep rising limb followed by a relatively gradual recession limb. This hydrograph shape indicates that rainfall runoff is quickly concentrated into the river channel, causing a rapid increase in discharge, while the recession process occurs more slowly as water stored within the watershed gradually drains back to the river system. Similar hydrograph characteristics have also been reported in previous studies applying the Nakayasu HSS method in watersheds with limited discharge observations.

The increase in peak discharge with increasing return periods indicates that higher rainfall magnitudes significantly affect flood potential in the Alo Watershed. The estimated design flood discharges obtained in this study can therefore provide important information for planning flood control infrastructure, such as river normalization, embankments, and drainage improvement in Sidoarjo Regency, particularly in flood-prone areas such as Kalitengah and Ketapang Villages.

In addition, future changes in land use, particularly the expansion of residential areas, may further reduce infiltration capacity and increase surface runoff within the watershed. Climate variability, which may alter rainfall intensity and patterns, also has the potential to increase future flood risk. Therefore, continuous updating of hydrological data and periodic re-evaluation of design flood discharge are necessary to support sustainable flood management in the Alo Watershed.

One limitation of this study is the absence of observed streamflow data in the Alo Watershed, which prevented direct validation of the design flood discharge estimated using the Nakayasu Synthetic Unit Hydrograph (HSS) method. Consequently, the resulting design flood discharges should be interpreted as preliminary estimates for flood mitigation planning purposes. Future studies are recommended to incorporate observed streamflow data or to compare results with other synthetic unit hydrograph methods to improve the reliability of flood discharge estimation.

4. CONCLUSION

Hydrological analysis of the Alo Watershed successfully generated a design flood discharge through areal rainfall analysis, frequency analysis, effective rainfall calculation, and flood hydrograph formation using the Nakayasu Synthetic Unit Hydrograph (HSS) Method. Areal rainfall was obtained by weighting Thiessen Polygons based on seven rainfall stations: Gedangrowo, Kludan, Porong, Budugbulus, Putat, Krembung, and Kedungcangkring, which represent the rainfall conditions of the Alo Watershed during the 2016–2025 observation period.

Frequency analysis using the Type III Log Pearson Distribution yielded a design rainfall that passed the distribution suitability tests using the Chi-Square and Smimov-Kolmogorov methods at the 5% significance level, making it suitable for hydrological analysis of the Alo Watershed. The design rainfall was then converted into a 6-hour hourly rainfall distribution using the Mononobe Method and calculated as effective rainfall with a runoff coefficient of 0.204.

Based on the effective rainfall distribution, the Nakayasu HSS Method produces a flood hydrograph plan with a peak discharge occurring at the second hour for all return periods of 2, 5, 10, 25, and 50 years. The peak discharge shows an increasing trend with increasing return period, reflecting the influence of higher design rainfall on the hydrological response of the Alo River Basin. The results of this study provide a flood design discharge that can be used as a basis for planning flood control structures and as input data for hydraulic analysis in the Alo River.

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