Rainfall-Runoff Simulation Using HEC-HMS Model in the Benanain Watershed, Timor Island

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ABSTRACT Floods in a watershed area are caused by reduced water recharge due to changes in land use, increasing their discharge volume. Benanain watershed is an extensive area with many tributaries. Watershed morphometrics provides initial information about the hydrological behavior and the hydrograph shape of flooding in these areas. Furthermore, rainfall-runoff modeling uses as a unit to approach the hydrological values of the flooding process. This study determines the physical characteristics of the Benanain watershed based on curve number (CN) values, land cover, peak discharge, and peak time. It was conducted on the Benanain watershed with 29 sub-watersheds covering 3,181.521 km². Data were collected on the rainfall experienced for 13 years from 1996 to 2008 and analyzed using the Log Pearson Type III method, while the HEC HMS model was used for flood discharge analysis. HEC-HMS model must calibrate by adjusting the model parameter values until the model results match historical data such as initial abstraction, lag time, recession, baseflow values, and curve number. The results show that the curve number values range from 56.55 - 73.90, comprising secondary dryland forest and shrubs. Moreover, the rock lithology in the Benanain watershed is dominated by scaly clay and other rock blocks. This means the area has low to very low permeability, which affects the volume of runoff. The return period of a 1000-year flood discharge obtained a peak of 5,794.50 m³/s, with a peak time of ± 14 hours. Morphometry of the Temef watershed with large catchment, radial shape pattern, an average of steep slope river, and meandering affects the peak of flood discharge hydrograph and the peak time of the flood.

KEYWORDS Run off; Curve Number; Radial; Permeability; Rock Lithology.

1 INTRODUCTION

A watershed is a catchment area with a unit river and tributaries accommodating, storing, and flowing water from rainfall to lakes or the sea. The land boundary is known as topography, while the sea boundary consists of the water areas affected by land activities (UU No. 7, 2004). Additionally, a watershed could be considered a hydrological unit because it converts rainfall (input) into runoff (output), sediment, and nutrients. The rainfall-runoff is a very complex scientific process influenced by several factors. Chow *et al.* (1998) explained that climatic and physiographic factors have the most significant influence on rainfall-runoff. Climatic factor includes the relation between rainfall and evapotranspiration, while physiographic factor influences comprise river

and watershed characteristics. Rainfall is an important meteorological parameter to determine river flow discharge. Furthermore, the runoff is influenced by the watershed's physical characteristics, including land use and soil. The watershed physical parameter could be expressed as an index of a curve number (CN). According to McCuen (1998), the CN value shows the effect of hydrology on soil, land use, and soil moisture.

Surface runoff is needed to determine the potential of water resources in the watershed. Tivianton (2008) stated that river flow discharge is the total surface runoff, rainwater directly falling on the river body, intermediate flow, and baseflow, measured at the river outlet point. The

flood hydrograph is used to analyze watershed rainfall-runoff watershed. According to Sene (2008), flood hydrographs are useful for studying river volume fluctuations and the discharge peak time to obtain a relationship between rainfall and river flow discharge by return period.

Some ungauged watersheds have insufficient flow data to be used in expressing flood hydrographs due to field conditions. In this case, quantitative analysis is carried out using a hydrological model. The Hydrologic Engineering Center - Hydrologic Modeling System (HEC-HMS) was developed by the U.S. Army Corps of Engineers (USACE) to simplify complex watershed systems. This assumption must be fulfilled for the model's input and output to suit the actual watershed system. Therefore, HEC-HMS simulates the flow calculation based on rainfall and watershed characteristics as input components. The watershed characteristics include morphometric aspects, land use, and soil conditions.

Several previous studies examined smaller watershed rainfall-runoff simulation in Indonesia using the HEC-HMS model (Sarminingsih *et al.*, 2019; Anggraheni *et al.*, 2018; Delani *et al.*, 2016). HEC-HMS is used widely with ArcGIS 10.5 software in spatial-based hydrological simulation with distributed data, continuous flow models, and calibration facilities. This software initially calculates losses, transformation (hydrograph unit), baseflow, and flood routing (Adidarma, 2013). Moreover, the Soil Conservation Service method shows the difference between total rainfall and actual evapotranspiration. It is useful in areas with rainfall but no flood hydrograph data, such as the Benanain watershed, due to lack of observation discharge or automatic water level recorder (AWLR).

The Benanain river is one of the largest and longest in East Nusa Tenggara Province (NTT), covering around 3181.521 km². The length of the main river is about 128 km and has around 92 tributaries. There are 13 large and 79 small rivers, while the Benanain river flows across four districts, including South Central Timor (TTS), North Central Timor (TTU), Malaka Regency, and Belu Regency. Its upstream is in the TTS, TTU, and Belu regencies, while the downstream is in the Malaka Regency, flowing into the Timor Sea.

Benanain river overflows almost annually and sometimes more than once a year, depending on the upstream rainfall intensity. The maximum runoff (floods) is caused by several factors, including high-intensity rain and the river's reduced cross-sectional capacity. Subsequently, the river channel dimensions become insufficient to accommodate the river flow. This results in overflows that inundate residential homes in West Malaka District.

Control efforts are needed to reduce the damage caused by floods in the watersheds, though this requires prior knowledge on flood discharge. Therefore, this study determines the physical characteristics of the Benanain watershed based on curve number (CN) values, land cover, peak flood discharge, and time. It uses the Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) Modeling.

1.1 Flood Hydrograph Analysis with the HEC-HMS Model

HEC-HMS (Hydrologic Engineering Center - Hydrologic Modeling System) software was developed by the U.S Army Corps of Engineering. It is a mathematical model that simulates the rainfall-runoff of a dendritic watershed system with basin and meteorologic models, as well as control specifications and data input (Bimtek Balai Bendungan, 2019).

HEC-HMS uses a synthetic unit hydrograph calculation method with measured and model flood hydrographs. The measured flood hydrograph was developed using the rainfall-runoff data. In comparison, the flow discharge is determined by the automatic water level recording (AWLR), using the rating curve equation. Additionally, this synthetic unit has several choices methods, such as the Soil Conservation Service Unit Hydrograph (Suhartanto, 2008). This method is accepted and applied because it is predictable and conceptually stable. Also, it has been tested and analyzed based

on its capabilities, limitations of use, as well as conceptual and empirical validity (Moglen 2000; Mishra *et al.* 2013; Banazik *et al.*, 2014; ZeenatAra & Zakwan, 2018).

The Soil Conservation Services method with a Curve Number estimates cumulative rainfall, land cover and use, and previous soil moisture. Curve Number (CN) is a function of the total rainfall thickness and a parameter for the runoff curve. CN values range between 1 and 100 as a runoff function resulting from basins or raised areas, such as hydrological soil types (NEH, 2004a), land use (NEH, 2004b), soil surface, and previous soil moisture (Adidarma, 2013; Ramadan *et al.*, 2017; Rao, 2020).

Table 1. Hydrological Soil Group Based on USDA Soil Classification

HSG	Soil Texture
A	Sand, loamy sand, or sandy loam
B	Silt or loam
C	Sandy clay loam
D	Clay loam, silt clay loam, sandy clay, or clay

Source: NEH, 2004a

1.2 The Curve Number from Rainfall-Runoff Data

The empirical formula used is shown in Equation (1).

$$P_e = \frac{(P - Ia)^2}{P - Ia + S} \tag{1}$$

where P_e is the accumulated runoff at time t (mm), P is the accumulated rainfall at time t (mm), Ia is the initial abstraction or loss (mm), and S is the potential maximum retention of rain in the watershed following the fulfillment of Ia (mm). Initial abstraction is the amount of rainfall that wets the soil surface, including crops, trash, and vacant land before actual infiltration begins. The empirical equations of Ia and S are linked linearly by λ, which is equal to 0.2 (Equation (2)).

$$Ia = 0.2\, S \tag{2}$$

Excess of rainfall during the Δt interval is the difference between accumulative rainfall at the end and beginning of the period. The potential maximum retention, S, and watershed characteristics were related to the intermediate parameter in Equation (3).

$$S = (25400 - 254\, CN)/CN \tag{3}$$

The SCS UH method determines the peak time (t_p, time to peak) and peak discharge (Q_p) shown in Equation (4) (USACE, 2000):

$$Q_p = C\frac{A}{t_p} \tag{4}$$

Where A is the watershed area, and C is the constant conversion (2.08 in the SI and 484 in the leg system). The peak time to the duration of the rainfall is shown in equation (5).

$$T_p = \frac{\Delta t}{2} + t_{lag} \tag{5}$$

Where Δt is the rainfall duration (hour) and t_{lag} is the time lag (hour). The equation for the time lag in hours is shown in Equation (6).

$$t_{lag} = \frac{L^{0,80} x\ (2540 - 22,86\ x\ CN)^{0,70}}{14104\ x\ CN^{0,70}\ x\ Y^{0,50}} \tag{6}$$

where L is the hydraulic length (the distance along the mainstream to the furthest point in meter units), Y is the mean slope of the watershed (m / m), and CN in the Curve Number.

2 METHODS

The Benanain watershed area is located on the island of Timor at the coordinate position of 124°11 '45.64" - 125° 07' 31.22" E and 8° 56'33.21" LS - 9 ° 58' 34.60" S (Figure 1). The data used in this study include:

a) Primary data:

Documentation and survey of flood questionnaires on local residents.

b) Secondary data:

Rainfall data and map data consist of:

1) Land cover map
2) Maximum daily rainfall from 1996-2008 (Balai Sungai Nusa Tenggara II)
3) Coordinates for the location of the rainfall station (Balai Sungai Nusa Tenggara II)
4) Map of the division of the UTM Zones in the Indonesian Territory
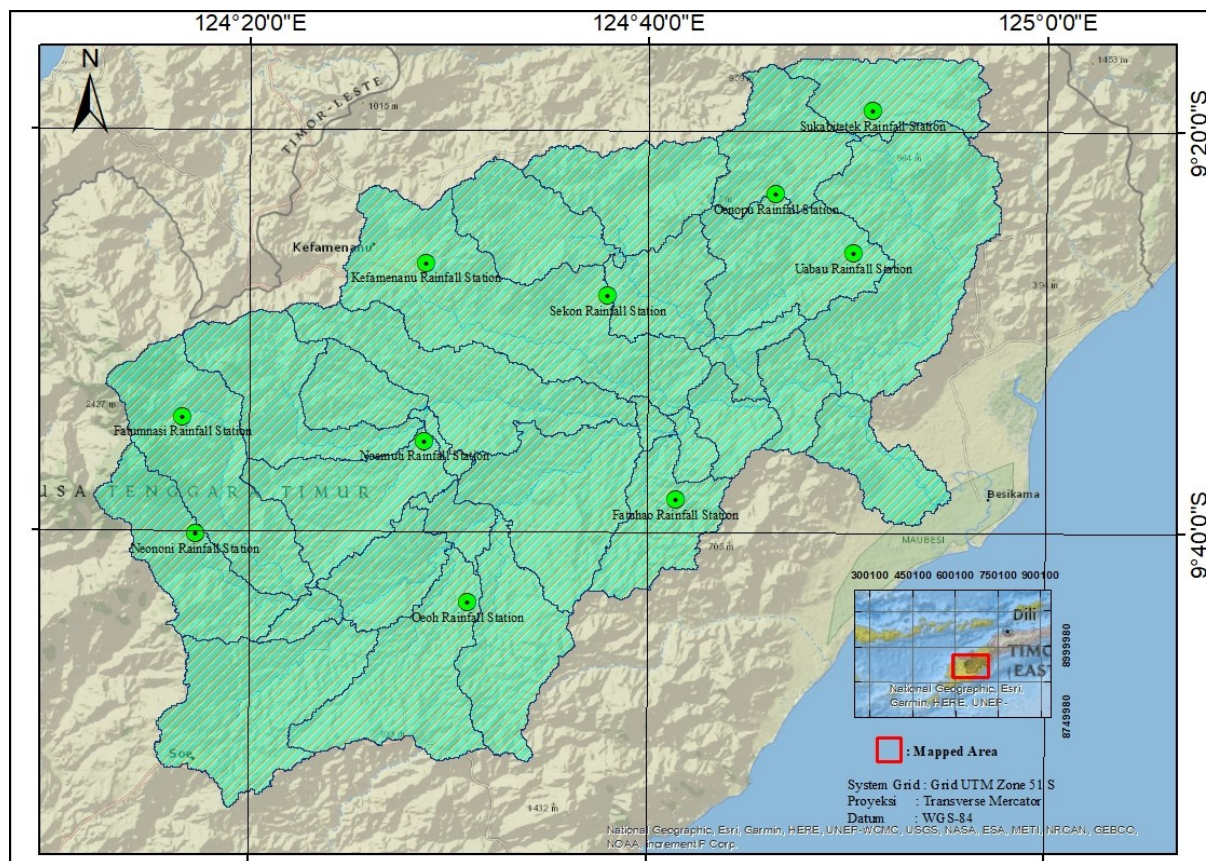5) Indonesian Hydrogeological Map (Directorate of Environmental Geology)

Figure 1. Location Map of Benanain Watershed.

ArcGIS 10.5 software digitization data consists of:
1) Data Digital Elevation Model / DEM (Software Global Mapper v.18)
2) The outlet points of the Benanain watershed (Google Earth)

The steps of the research carried out were as follows:
a) Hydrological analysis by collecting rainfall data for 13 years (1996-2008) from ten rainfall stations in the Benanain watershed, as shown in Figure 1.
b) Digitizing watershed parameters, including boundaries, area, length of the main river and tributaries, number of confluences, slope, watershed width, and basin modeling with the ArcGIS 10.5 software.
c) Digitizing land cover and hydrological soil grouping. This step involves calculating the curve number value by diversifying from a hydrogeological to a hydrologic soil group map.
d) Calculating the flood discharge using the Soil

Conservation Service Curve Number (SCS-CN) method with the software tools of the Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) 4.3.

3 RESULTS

3.1 Hydrology Analysis

The calculation of rainfall distribution for the Benanain watershed uses four methods for each station. These are the Normal distribution method, Log-Normal, Log-Pearson Type III, and Gumbel. The results were obtained by the goodness of fit test with the chi-square and Smirnov Kolmogorov. The recapitulation of the design rainfall analysis is in Table 2.

Triatmodjo (2008) stated that the distribution to be used must adjust to the requirements of skewness coefficient (Cs), variation coefficient (Cv), and kurtosis coefficient (Ck) according to Table 3. Digitization using ArcGis 10.5 resulted in the Benanain watershed area of 3,181.521 km², divided into 29 sub-watersheds from W-300 to W-580, as shown in Figure 2.

Table 2. Recapitulation of Design Rainfall by Return Period Using Various Methods in the Benanain Watershed

Return Period (Years)	Normal distribution	Log-Normal Distribution	Log-Pearson Type III Distribution
2	77.85	71.42	72.77
5	104.96	103.59	104.13
10	119.16	125.87	124.26
25	132.98	152.15	148.93
50	144.01	177.00	166.75
100	153.05	200.36	184.03
500	170.80	255.60	212.42
1000	177.57	280.51	239.62

Table 3. Statistical Parameter Test

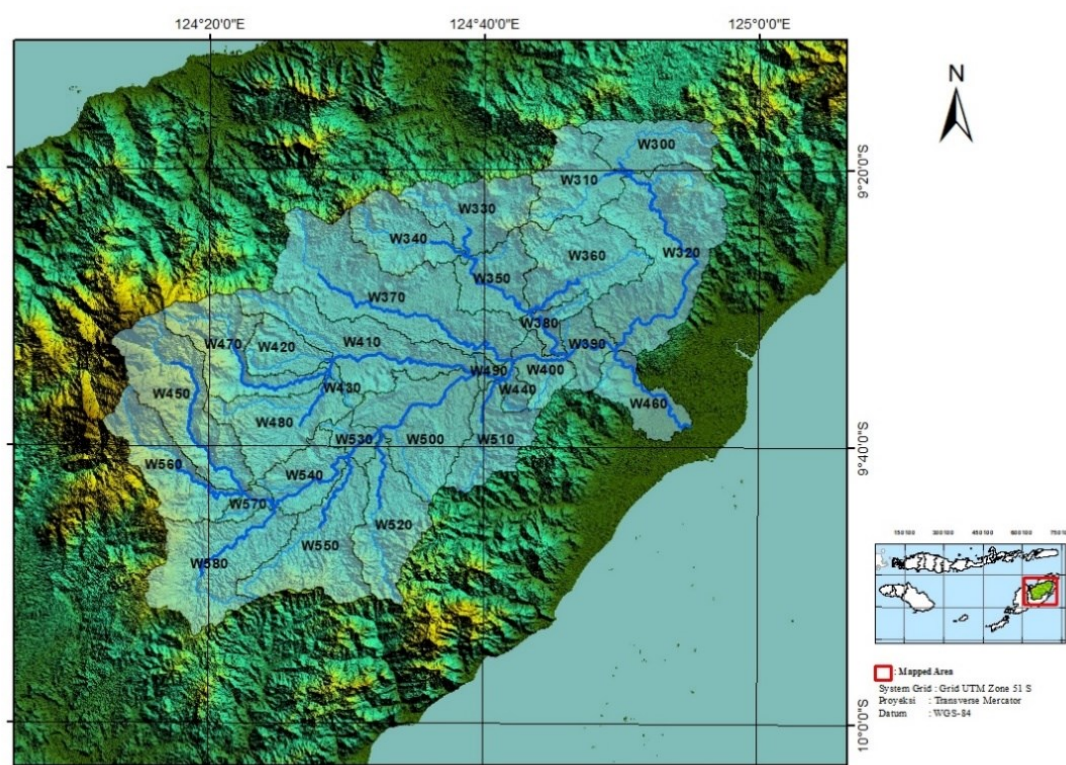| Distribution	Parameters	
	Required	Obtained
Normal	Cs = 0.0000	Cs = 0.2300
	Ck = 3.0000	Ck = 0.0015
Log-Normal	Cs/Cv = 3.00	Cs/Cv = -2.45
Gumbel	Cs = 1.1396	Cs = 0.2300
	Ck = 5.4002	Ck = 0.0015
Log-Pearson Type III	-	Cs = -0.2500
		Ck = 0.1000

Figure 2. The Map of Benanain Sub-Watershed.

3.2 Analysis of Land Cover and Curve Number (CN) Value of the Benanain Watershed

The curve number value represents the watershed physical characteristics of soil, hydrological conditions, land use, and antecedent moisture condition (AMC). The Land Use Map of the island of Timor could be used to classify and analyze the land use of the Benanain watershed using ArcGIS 10.5 software. The Benanain watershed has 9-types of land cover, including primary and secondary dryland forest, agriculture, shrubs, savanna, scrub, open land, settlement, and water

bodies. The CN value was determined using the SCS-CN method by combining land use with the Hydrologic Soil Group (Krisnayanti *et al.*, 2021). Additionally, the soil hydrology group is divided into A, B, C, and D based on their textures. The external texture determines the hydrological group because it relates to the soil's effective water capacity and affects infiltration. The results from the calculation of curve number analysis for the 29 sub-watersheds are shown in Figure 3.

3.3 Surface Runoff in the Benanain Watershed

Flood hydrograph analysis with the HEC-HMS model involved determining the highest single

peak flood hydrograph events and a single rain during a certain period. According to Ponce (1989), the intensity rainfall greater than 10 mm is considered heavy rain, possibly causing floods. It is necessary to fill hydrological parameters in the HEC HMS, including basin and meteorological models, control specifications, time-series data, losses, transform base flow, and river routing. These parameters are needed to determine the flood discharge value by return period in the Benanain watershed. The recapitulation flood discharge design for various returns periods (W460) is shown in Table 4. The results in Table 4 were then plotted into then in Figure 4.
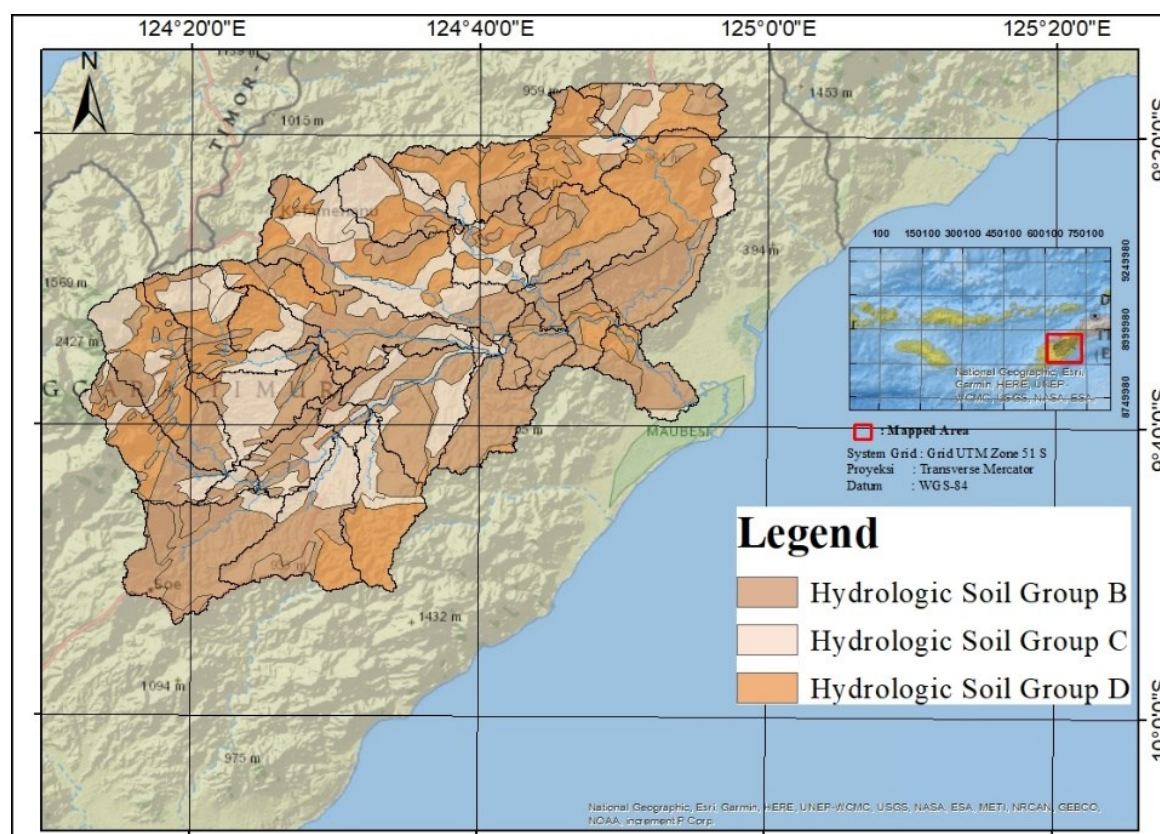

Figure 3. Hydrologic Soil Group (HSG) map in the Benanain watershed

Table 4. Recapitulation of flood discharge by return period in the Benanain watershed

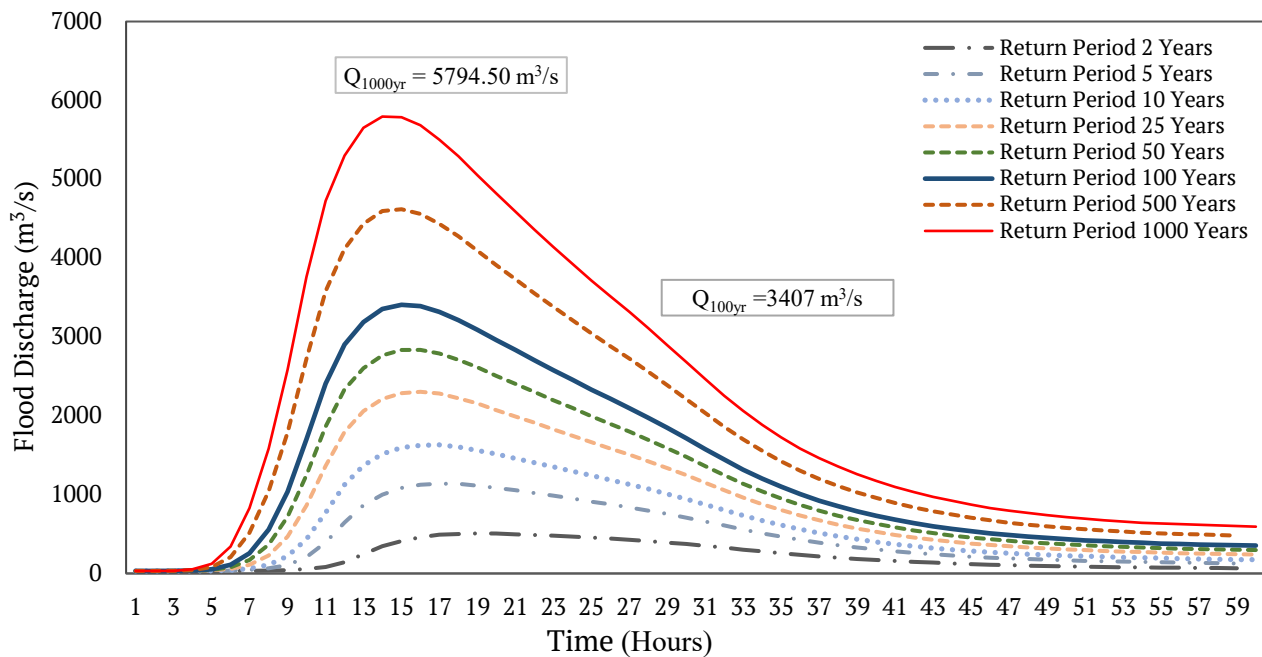| No	Return Period (Years)	Flood Discharge (m³/s)	Inflow from W- 460 (m³/s)
1	2	507	495
2	5	1138	1106
3	10	1631	1583
4	25	2304	2225
5	50	2835	2730
6	100	3407	3265
7	500	4619	4405
8	1000	5794	5493

Figure 4. Design Flood Discharge by Return Period of 2 – 1000 Years in the Outlet of Benanain Watershed

4 DISCUSSION

The Log-Pearson Type III distribution is a statistical technique used in hydrology analysis from the four methods in Table 2. It fulfills the required statistical tests and has no limit value on the coefficient of variation (Cv) and the coefficient of skewness (Ck). The calculations using this method obtained a coefficient of variation (Cv) of 0.10 and the coefficient of skewness (Cs) of -0.25. Therefore, the method is useful in calculating the design flood discharge by a return period of 2-1000 years.

The land cover in the Benanain watershed is dominated by secondary dryland forests and shrubs, with respective percentages of 44.26% and 22.53%. Open land cover and water bodies had the smallest percentages of 1.00% and 0.01%, respectively. Furthermore, Figure 3 shows that the CN value of the Benanain watershed ranges from 56.55 to 73.90. The largest CN is in sub-watershed W-310, dominated by scaly clay, rock boulders, and shrubs. The smallest CN is in sub-watershed W-510, covering 87.98 km² or 0.91%. The area is dominated by sandy marl interbedded with sandstone, conglomerates, dacitic tuff, and open forest land cover.

Figure 4 shows that the flood discharge for a 1000-years return period is 5,794.50 m³/s with a peak time of ± 14 hours. The Benanain watershed is radial or fan-shaped, and its tributaries are concentrated at an outlet downstream. Watersheds with this pattern often have heavy flooding near the tributary's outlet points. This study shows discharge values similar to the previous research, using different methods in the same area. For instance, Balai Wilayah Sungai NT II (2014) examined the flood discharge in the Benanain watershed using the Nakayasu and Snyder Synthetic Unit Hydrograph methods. The study focused on the flood design for a 100-year return period and obtained 3,635.00 – 3,959.00 m³/s. In comparison, this study analysis found that the 100-year return period for Benanain watershed flooding was 3,407.10 m³/s. The insignificant disparity in these results was influenced by different input parameters for each method used.

Flood discharge occurs because the Benanain watershed covers around 3,181.521 km², with curve numbers ranging between 56.55 and 73.90. Furthermore, the hydrogeological map of Timor Island shows that the Benanain watershed is dominated by scaly clay and other rock blocks. The area has low to very low permeability, affecting runoff compared to water infiltration. The watershed morphometrics, such as land

cover, soil type, area, slope, shape, and river patterns, provide relevant initial information about the flood hydrograph. However, the results of this simulation discharge would be better when calibrated with field observations. The unavailability and unreliable observation discharge data is an obstacle in calibrating with the simulation discharge. Therefore, it is necessary to calibrate the simulation discharge against the observation discharge for further analysis.

5 CONCLUSION

The Benanain river is one of the largest and longest in NTT Province, divided into 29 sub-watersheds. Its land cover is dominated by secondary dryland forest and shrubs, with respective percentages of 44.26% and 22.53%. Moreover, the watershed's lithology is dominated by scaly clay, containing other rock blocks with low to very low permeability. The area is classified under the HSG D group, with an area percentage of 25.667%. The 1000-year return period of flood discharge using SCS CN obtained a peak discharge of 5,794.50 m^3/s. It is the same as the discharge analyzed by previous studies of 7-15% from the simulation discharge using the HEC-HMS model and the SCS-CN method. However, this simulation would be better when calibrated with field observations. Moreover, the long rainfall-runoff record data would show a better comparison between the HEC-HMS model results and actual conditions.

DISCLAIMER

The authors declare no conflict of interest.

AVAILABILITY OF DATA AND MATERIALS

All data are available from the author.

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