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Intensity-Duration-Frequency (IDF) Curve and the Most Suitable Method to Determine Flood Peak Discharge in Upper Werba Sub-Watershed

Kusumastuti, C.[1]*, Sudjarwo, P.[1], Christhie, M.[1], and Krisna, T.[1]

Abstract: Design flood is one of the important factors for flood risk assessment and water infrastructures planning and development in a certain location. There are several methods to estimate it, one method which has been commonly and widely use is using flood frequency analysis. This research aims to develop Intensity-Duration-Frequency (IDF) curves in Upper Werba Sub-Watershed, West Papua Province, Indonesia, to estimate design rainfall intensity. The design rainfall intensity is used to estimate peak of flood discharge using Rational Formula in the sub-watershed. Other methods, i.e. Soil Conservation Service and Nakayasu Synthetic Unit Hydrograph are also presented in this paper to provide comparison of the estimated peak of flood discharge. The result shows that the Rational method provide the closest magnitude of estimated flood discharge in Upper Werba Sub-Watershed to the observed streamflow. Therefore, it is suggested that the Rational method can be used for water infrastructure planning and development in the sub-watershed.

Keywords: IDF curve; rational method; stream flow; synthetic unit hydrograph; watershed.

Introduction

Information of design flood is one of important factors for flood risk assessment and water infrastructures planning and development in a certain location [1]. Many approaches have been used to estimate it including flood frequency statistics and the design storm method [2]. Rogger et al. [2] mentioned that geological information on the catchments is important to identify the mismatch of flood discharge estimation and flood discharge observed.

Flood frequency analysis is a well-established approach which has been applied in decades [1,3-5]. This analysis is still commonly used until recently. Hailegeorgis and Alfredsen [6] used L-moments method and annual maximum series for flood quantiles prediction ungauged basins in mid-Norway and Ozga-Zielinski et al. [7] used two-dimensional (2D) normal distribution and copula-based 2D probability distribution to estimate flood peak and flood volume in Narew River, Poland. Other method such as modelling of rainfall-runoff process presented in flood hydrograph can be used for flood discharge estimation.

[1] Department of Civil Engineering, Petra Christian University, Jl. Siwalankerto 121-131, Surabaya 60236, INDONESIA
*Corresponding author; email: cilcia.k@petra.ac.id

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Flood hydrograph can be derived from unit hydrograph at certain location. In order to develop a unit hydrograph for a certain location, specifically a watershed, detailed and complete historical data of rainfall and streamflow are needed. However, such data would not available in every watershed [1]. Therefore, Synthetic Unit Hydrograph can be generated.

Unit Hydrograph (UH) and Synthetic Unit Hydrograph (SUH) are the common methods applied to estimate flood discharge. Swain et al. [8] used Geomorphologic Instantaneous Unit Hydrograph (GIUH) and SUH to estimate streamflow in Koel River basin of India. Kusumastuti et al. [9] developed Soil Conservation Service Synthetic Unit Hydrograph (SCS SUH) in Ambon, Indonesia, to estimate peak of flood discharge and evaluate drainage channels capacity. Procedure of development of various SUHs have been discussed in detail in many hydrology handbooks, e.g. Snyder's SUH and SCS Dimensionless Hydrograph [1,3,4]; SCS Triangular Hydrograph [1]; GAMA I SUH and Nakayasu [4].

Indonesia is an archipelago country. It consists of more than 16,000 islands [10]. Papua Island is the biggest island located in the easternmost territorial of Republic of Indonesia. In the last few years, infrastructures planning in the area became important issue including water infrastructures. This paper aims to present the intensity-duration-frequency (IDF) curve for a certain watershed in West Papua Province as well as to compare several methods which provide the closest magnitude of the estimated flood peak discharge to the observed stream flow.

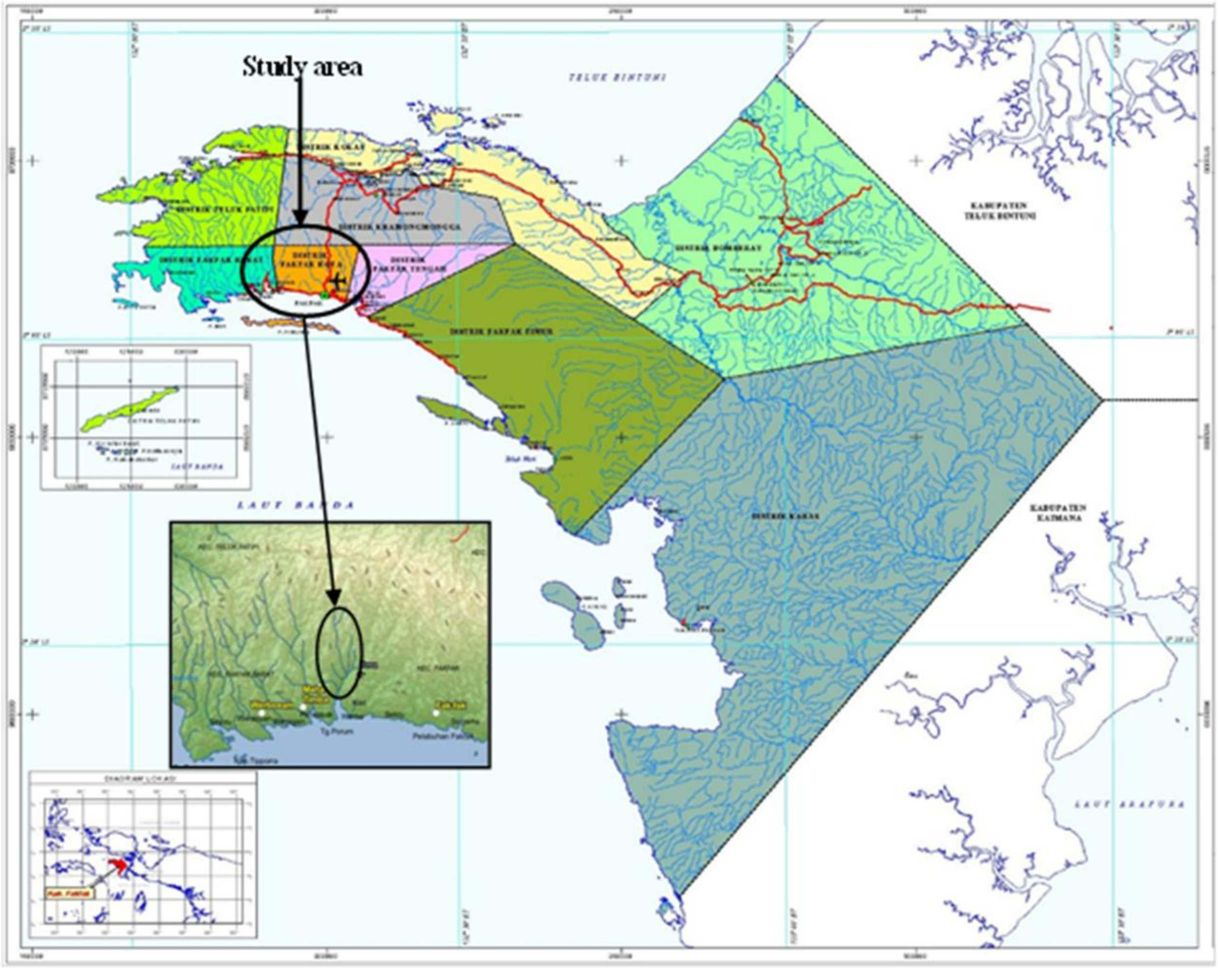


Figure 1. Location of Study Area (not to scale)

Study Area and Rainfall Data

Study Area

The study area of the research is Upper Werba Sub-Watershed. Werba River is flowing in Werba District, Fakfak Regency, West Papua Province, Indonesia, as can be seen in Figure 1. Fakfak Regency is located between 131°30' - 138°40' East Longitude and 2°25' - 4° South Latitude [11]. Werba River flows from Onin Mountain to Laut Seram (Seram Sea). Specifically, the watershed map in presented in Figure 2. The length of the river which is analyzed in this paper is 12.50 km with 28.02 km^2 catchment area.

Rainfall Data

Average number of rain day in Fakfak Regency is 269 days [11]. Daily rainfall data from 2009 – 2018 and hourly rainfall data in 2018 were collected from a meteorological station in Torea Airport, Fakfak Regency. The maximum daily rainfall from 2009 – 2018 is analyzed from those data and presented in Table 1.

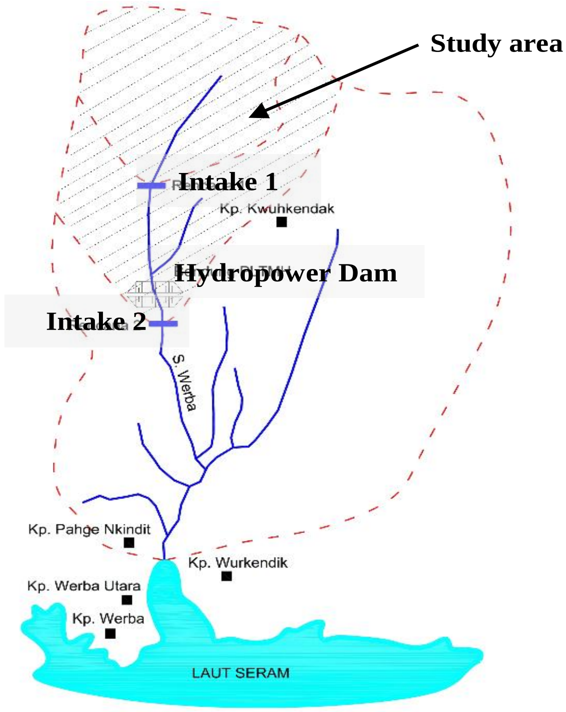


Figure 2. Werba Watershed (not to scale)

Table 1. Maximum Daily Rainfall in Fakfak Regency

No.	Year	Rainfall Depth (mm)
1	2009	184.0
2	2010	113.0
3	2011	184.0
4	2012	112.8
5	2013	144.2
6	2014	140.2
7	2015	154.0
8	2016	122.3
9	2017	136.3
10	2018	136.6

The frequency analysis of maximum daily rainfall data is conducted to observe the type of extreme value distribution. The coefficient of skewness and coefficient of kurtosis of the maximum daily rainfall data are 0.329 and 3.16, respectively. At those numbers, the distribution of the data is close to the characteristic of Log Normal distribution. Goodness of fit test, i.e. Chi-square test [3], is then conducted as a validation step. At 5% significant level and three degree of freedom, the value of Chi-suare, X^2, is obtained as much as 3. This calculated X^2 is lower than the critical value of chi-square distribution (X^2_{Cr} = 7.815), therefore statistical distribution of maximum daily rainfall data in Fakfak Regency follows Log Normal distribution.

Development of Intensity-Duration-Frequency (IDF) Curve

To develop intensity-duration-frequency (IDF) curve, rainfall intensity is transformed from daily rainfall data using Mononobe method [4] in Equation 1. The formula requires the information of time of concentration to transform rainfall depth into rainfall intensity (I).

$$I = \frac{R_{24}}{24}\left(\frac{24}{t}\right)^{\frac{2}{3}} \quad (1)$$

for:

I : rainfall intensity (mm/hour)

R_{24} : maximum daily rainfall at certain return period (mm)

t : time of concentration (hour)

In this research, the time of concentration is determined based on the average duration of rain in a day recorded in meteorological station in Torea Airport, Fakfak Regency in 2018. Based on one-year data of hourly rainfall in 2018, the average duration of rain in a day in Fakfak Regency is 3 (three) hours. The second component of Mononobe formula is R_{24}. By using Log Normal distribution function in Equation 2 [4], the design rainfall for 2, 10, 25, and 50-year return period is estimated and presented in Table 2. The result of conversion of design rainfall depth to design rainfall intensity using Mononobe formula is presented in Table 2.

Table 2. Design Rainfall at Various Return Period for Fakfak Regency

Return Period, T (year)	Design Rainfall (mm)	Rainfall Intensity (mm/h)
2	140.9	23.5
10	151.6	25.3
25	155.9	25.9
50	158.5	26.4

$$x_T = antilog\ (z_T) \quad (2)$$

for:

$z_T = \bar{z} + K_z\sigma_z$

$z = logx$

x_T : hydrologic parameter value at certain return period, T

σ_z : standard deviation of the Z variate sample

K_z : frequency factor of Log Normal distribution

IDF curve represents the information of intensity, duration, and frequency of rainfall. The frequency in this curve is shown by the return period of design rainfall. The IDF curves for Upper Werba Sub-Watershed at 2, 10, 25, and 50-year return period are presented in Figure 3.

The IDF curves in Figure 3 provide the important information of rainfall intensity which can be used to estimate flood discharge using Rational Method [1] in Upper Werba Sub-Watershed. Rational Method has been used previously by Kusumastuti et al. [12,], to estimate peak of flood discharge in several watersheds in Probolinggo Regency, Indonesia and Kusumastuti et al. [13] to estimate surface runoff volume for designing eco-drainage system in Mojokerto Municipality, Indonesia.

Flood Discharge Estimation

Flood frequency analysis is the main method to estimate flood discharge in Upper Werba Sub-Watershed in this research. There are three methods chosen, i.e. Soil Conservation Service SUH, Nakayasu SUH, and Rational Method. The estimated peak of flood discharge obtained through those methods is then compared with observed streamflow in Upper Werba River.

Soil Conservation Service SUH

To develop Soil Conservation Service (SCS) SUH, several data of river and rainfall characteristic, i.e. time of concentration, duration of effective rainfall, and catchment area are needed. Those data is used to estimate the peak of flood discharge using Equation 3 [3].

$$q_p = \frac{CA}{T_p} \quad (3)$$

for:

$$T_p = \frac{t_r}{2} + t_p$$

$t_p \cong 0.6\, T_c$
C : 2.08
A : catchment area (km^2)
T_p : time to peak (hour)
t_p : lag time (hour)
T_c : time of concentration (hour)

By using 3-hour time of concentration, the time to peak of flood discharge is 3.3 hours and the magnitude of peak of flood discharge in upper Werba River is as much as 1.778 m^3/s.cm. 1-hourly magnitude flood discharge is presented in Figure 4. For 2-year return period of design rainfall which is presented in Table 2., the estimated peak of flood discharge in Upper Werba Sub-Watershed by using SCS SUH is 25.06 m^3/s.

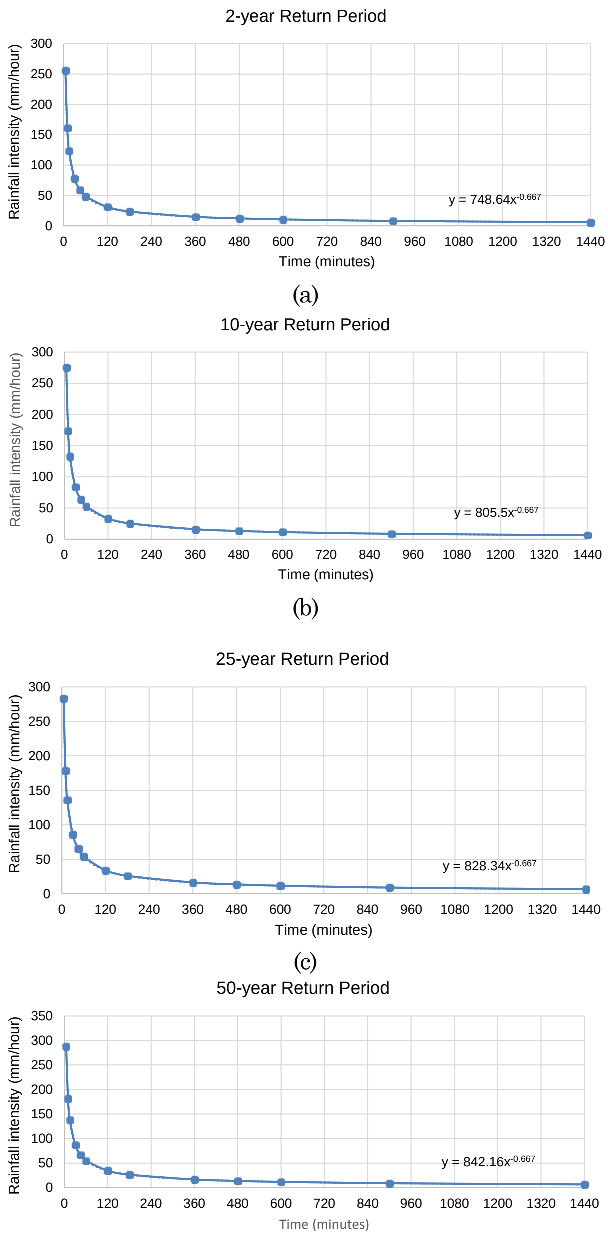


Figure 3. Intensity-duration-frequency curve for Fakfak Regency at various return period (a) 2-year; (b) 10-year; (c) 25-year; (d) 50-year

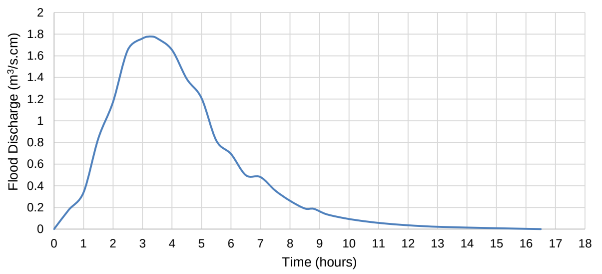


Figure 4. SCS Unit Hydrograph for Upper Werba Sub-Watershed

Nakayasu SUH

The second synthetic unit hydrograph (SUH) which is developed for Upper Werba Sub-Watershed is Nakayasu SUH. Information of length of the river and time of concentration are needed to develop Nakayasu SUH. The peak of flood discharge is estimated by using Equation. (4).

$$Q_p = \frac{A \cdot R_e}{3.6(0.3T_p + T_{0.3})} \tag{4}$$

for:
$T_p = T_g + 0.8T_r$
$T_g = 0.21\, L^{0.7}$ for L < 15 km
$T_g = 0.4 + 0.058\, L$ for L > 15 km
$T_r = 0.5\, T_g$ *up to* T_g
$T_{0.3} = \alpha T_g$
Q_p : peak of flood disharge (m^3/s)
T_p : time to peak (hour)
L : river length (km)
A : catchment area (km^2)
R_e : effective rainfall (mm)
α : watershed characteristic coefficient = 2

For 2-year return period of design rainfall in Table 2., the estimated peak of flood discharge by using Nakayasu SUH in the sub-watershed is 391.3 m^3/s. Unlike SCS SUH, the ordinate of rising limb (eq. 5) and falling limb of the unit hydrograph (eq. 6, 7, 8) of Nakayasu SUH are defined specifically [4].

For period of time of $0 < t < T_p$, the ordinate of rising limb (Q_n) is calculated using Equation (5).

$$Q_n = Q_p \left(\frac{t}{T_p}\right)^{2.4} \tag{5}$$

For period of time $T_p < t < (T_p + T_{0.3})$, the ordinate of falling limb (Q_t) is calculated using Equation (6).

$$Q_t = Q_p \times 0.3^{(t-T_p)/T_{0.3}} \tag{6}$$

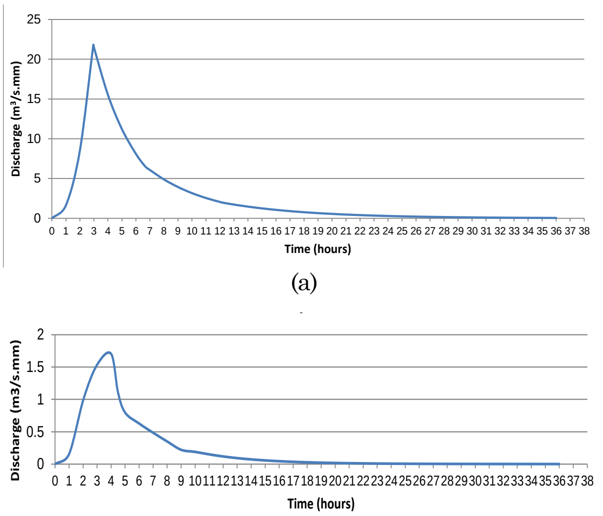
For period of time $(T_p + T_{0.3}) < t < (T_p + T_{0.3} + 1.5T_{0.3})$, the ordinate of falling limb (Q_t) is calculated using Equation (7).

$$Q_t = Q_p \times 0.3^{[(t-T_p)+(0.5T_{0.3})]/T_{0.3}} \tag{7}$$

For period of time $t > (T_p + T_{0.3} + 1.5T_{0.3})$, the ordinate of falling limb (Q_t) is calculated using Equation (8).

$$Q_t = Q_p \times 0.3^{[(t-T_p)+(1.5T_{0.3})]/(2T_{0.3})} \quad (8)$$

The first development of Nakayasu USH using 28.2 km² of catchment area, 12.50 km river length, and one-hour time of concentration produced the one-hour Nakayasu SUH which is presented in Figure 5(a). Due to the estimated time of concentration in Upper Werba River is 3 (three) hours, therefore, the one-hour Nakayasu SUH is transformed into three-hour SUH by using superposition method [4] and presented in Figure 5(b).



(b)

Figure 5. (a) 1-hour and (b) 3-hour Nakayasu SUH for Upper Werba Sub-Watershed

The 3-hour Nakayasu SUH shows that with three times longer of time of concentration in Upper Werba River, the time to peak occurred two hours late and the magnitude of peak of flood discharge is about 67% lower.

Rational Method

Rational method is commonly used in sewer design to estimate the peak of flood discharge using Equation (9). The information to be known for estimating peak of flood discharge using Rational method are runoff coefficient, rainfall intensity, and catchment area [1].

$$Q_p = \frac{1}{3.6} C\left(i_{tc,p}\right) A \quad (9)$$

for:

Q_p : peak discharge (m³/s)
C : runoff coefficient
$(i_{tc,p})$: intensity of precipitation (mm/h) for a duration equal to tc and an exceedence probability P
A : catchment area (km²)

Runoff coefficient is determined based on the land use of the catchment area. In this research, the percentage of land area and its utilization, as well as runoff coefficient for each land use in Upper Werba River in 2014 – 2018 is presented in Table 3. The C value which used in the Rational Formula is the composite value of runoff coefficient for all land utilization in the research area. Based on the presented data in Table 3, the composite runoff coefficient for Upper Werba Sub- is 0.353.

Table 3. Land use of Upper Werba Watershed 2014 – 2018

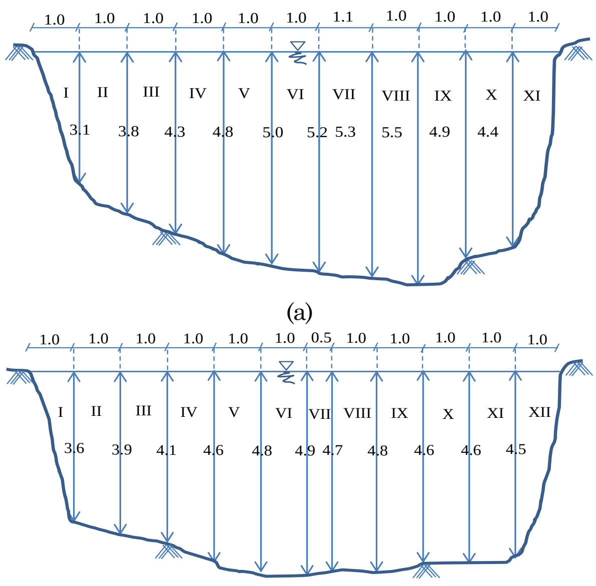
Land Use[11]	Area (%)*[14]	Runoff Coefficient*[4]
Productive forest	44.42	0.38
Conversion productive forest	22.02	0.35
Limited production forest	14.00	0.36
Protected forest	3.98	0.38
Nature conservation area	6.26	0.30
Others	9.22	0.25
Water Body	0.11	-

*Note: *estimated value*

Streamflow Measurement

The verification step in the research is done by comparing the estimated peak of flood disharge by using SCS SUH, Nakayasu SUH, and Rational Method at 2-year return period to the measured streamflow in upper Werba River which is presented in Table 4. The measurement of streamflow was conducted for 100 m length of river at 10 m-upstream of Intake 2 (Figure 2).

The streamflow measurement was done in May 2019. It covered the measurement of average velocity and depth of flow. The measured average velocity in the location of measurement is 1.38 m/s and the depth of flow is presented in Figure 6. By multiplying the average velocity and average cross sectional area of the river, the measured streamflow is obtained as much as 66.19 m³/s.



(b)

Figure 6. (a) Upstream and (b) Downstream Cross Sectional Area at the Location of Streamflow Measurement

The expected result of estimated peak of flood discharge at 2-year return period by using certain method is close to the measured streamflow. The results presented in Table 4 show that the Rational method provides the closest magnitude to the measured discharge at 1.8% difference.

Table 4. Discharge Comparison in Upper Werba River using Various Method

	Qmeasured	Qp Nakayasu	Qp SCS	Qp Rational
(m^3/s)	66.19	391.30	25.06	65.00
% different	-	491.2	62.1	1.8

Conclusions

The research has developed 4 (four) IDF curves at 2, 10, 25, and 50-year return period for Upper Werba Sub-watershed. It is expected that the IDF curves could be used for further water infrastructures planning and development in the area. The research also has presented 3 (three) methods to estimate peak of flood discharge, i.e. SCH SUH, Nakayasu SUH, and Rational method. From those three methods to estimate the peak of flood discharge, Rational method provides the closest magnitude to the measured streamflow in Upper Werba River. Therefore, it is suggested that the Rational method can be used for other purposes in water infrastructures planning and development in the sub-watershed.

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