DOI: 10.1515/jwld-2017-0082

JOURNAL OF WATER AND LAND DEVELOPMENT
2017, No. 35 (X–XII): 173–183
PL ISSN 1429–7426

Available (PDF): http://www.itp.edu.pl/wydawnictwo/journal; http://www.degruyter.com/view/j/jwld

Received 15.03.2017
Reviewed 19.07.2017
Accepted 24.07.2017

A – study design
B – data collection
C – statistical analysis
D – data interpretation
E – manuscript preparation
F – literature search

Conformity evaluation of synthetic unit hydrograph (case study at upstream Brantas sub watershed, East Java Province of Indonesia)

Dwi PRIYANTORO ADF, **Lily Montarcih LIMANTARA** BCE ✉

University of Brawijaya, Faculty of Engineering, Department of Water Resources, Jl. Mt Haryono No. 167, 65145 Malang, East Java Province, Indonesia; e-mail: lilymont2001@gmail.com

For citation: Priyantoro D., Limantara L.M. 2017. Conformity evaluation of synthetic unit hydrograph (case study at upstream Brantas subwatershed, East Java Province of Indonesia). Journal of Water and Land Development. No. 35 p. 173–183. DOI: 10.1515/jwld-2017-0082.

Abstract

This study intends to analyse the suitable hydrograph in upstream Brantas sub watershed. The methodology consists of comparing the result of hydrograph due to the methods of Nakayasu synthetic unit hydrograph (SUH), Limantara synthetic unit hydrograph, and the observed unit hydrograph. In detail, this study intends to know the difference of hydrograph parameters: α and Tg as recommended by Nakayasu and in the study location; to know the influence of main river length which is used in the methods of Nakayasu and Limantara to the time of concentration; to know the hydrograph ordinate deviation between Nakayasu and Limantara due to the observed hydrograph. Result is hoped for recommending the suitable hydrograph in upstream Brantas subwatershed so that it can be used accurately for the further design of water resources structure.

Key words: *Limantara method, Nakayasu method, observed hydrograph, synthetic unit hydrograph (SUH)*

INTRODUCTION

More than 50% of water disasters worldwide are floods, and most of people annually are exposed to catastrophic flooding. Floods are as natural disasters which is causing functional damages to critical infrastructures, transportation, and communications. Otherwise they are causing damages to any property and facilities [KALYANAPU *et al*. 2009]. To compare with the other natural disasters (like droughts, landslides, volcanic eruptions, forest fires, etc.), floods have the greatest destructive potential and influence people throughout the world [WAŁĘGA 2013]. There are several factors which are contributing to the flooding problem. It is ranging from topography, drainage, engineering structure, and climate. Most floods are caused by storms in which a lot of precipitation fell in a short period of time [PRADHAN 2009]. Duration and intensity of the rain are the most affecting factors for flood hazards. Human activities such as major land use changes, uncontrolled construction of buildings, and development of unplanned rapid settlement can affect the temporal and spatial pattern of hazards.

Design purposes on watersheds with limited data needed the estimation of peak discharge that is as a problem in hydrology continuously. Estimation of direct runoff in a watershed is needed for water resources system planning [DUTTA *et al*. 2006]. The characteristic of hydrological processes governing direct surface runoff which varies both in time scales and space. However, model of rainfall is differentiated between high flow and low flow due to the intensity events [LIMANTARA 2010a]. Rainfall-runoff models are used in hydrology for a wide range of application on estimation of flow, the extension of stream flow records, observation and evaluation of climate change impact, and prediction of land use change effect [NANDAKUMAR, MEIN 1997]. Structural and non-structural approached are implemented to mitigate the impacts of floods. Hydraulic and hydrologic models are used to plan and develop structural and non-structural flood mitigation.

Models of flood has been developed from the estimation of peak discharge and time to peak approached to multi-dimensional, multi-scale distributed models capable of representing the flood flows over a watershed surface [KALYANAPU *et al.* 2009]. One of the major problems in applied hydrology related to floods is the prediction of flood which is produced from heavy rain over a catchment. Design of hydraulic structure demands the reliable information that is concerning the design flood or peak flow which is expected after a given probability of occurrence and return period. In this sense, the hydrologist often faces with predicting extreme flood events on the basis of historical flood records [YUREKLI *et al.* 2004]. Regardless of history in flood model, an important characteristic in watershed has been known as the unit hydrograph.

The hydrological approaches in the watershed systems has granted great many contributions to the hydraulic structures planning [LIMANTARA 2009b], though it was still difficult to understand thoroughly the process of rainfall-runoff. Rainfall-runoff forecasting widely uses the instantaneous unit hydrograph (IUH) concept. Consequently, the IUH method should still be used either on its own or as a component in more complex conceptual models [HOYBYE, ROSBJERG 1999]. Several observations and investigations develop models for IUH from the multi periods events [PRASAD *et al.* 1999]. These investigations are ever since the inception of unit hydrograph (UH) by Sherman in 1932 [VIESSMAN *et al.* 1977]. Researchers have come up successfully with models which in nowadays hydrology are known well as the synthetic unit hydrographs (SUH).

Synthetic unit hydrograph (SUH) could become the source of some important information that is needed for the reliable of hydraulic structures [VIESSMAN *et al.* 1977]. However there are some kinds of SUH which were founded by researchers in the world, such as SUH Nakayasu (researched in Japan), SUH Snyder (researched in USA), SUH Gama I (researched in Indonesia), SUH Limantara (researched in Indonesia), etc. [LIMANTARA 2010b]. Though in fact, the application of these model on the Java Island still firstly requires calibration of several parameters. Realizing that SUH models has been researched in areas which the watersheds were far different than the ones applied. They therefore quite often come up with inaccurate result, which affects the design of hydro structure. Ideally, every watershed has to have its own particular unit hydrograph [LIMANTARA 2009a].

Nowadays, development of human civilization will not be able free from the water function as one of the main supporting. One of the important factors in designing water structure as described above is the value of design flood [NANDAMUKAR, MEIN 1997; YUE *et al.* 2002] which the value determines the dimension of structure and very related with the risk of structure economic value. For the needs, there are some methods which are recommended by hydrological experts from any countries due to the type and available number of data like Nakayasu (Japan), Snyder (USA), Gamma I (Indonesia), Limantara (Indonesia) etc. To remember that there widely usage of Nakayasu method nowadays and in reality there are any difficulty in application in watersheds of Indonesia, so this study intends to solve the problem [LIMANTARA 2009a, b]. Synthetic unit hydrograph of Limantara is a new method and it has not more been used in analysis of design flood. But this method is founded due to the research in some watersheds in Indonesia [LIMANTARA 2010a]. However, synthetic unit hydrograph of Limantara can be applied in any watersheds by attending the technical specification as the range boundary of data which are used for analysing by using Limantara method.

This research has the limitations as follow: 1) the models methods which are used for analysis of design flood are synthetic unit hydrograph of Nakayasu and Limantara and then the results are compared to the observed hydrograph; 2) research location is in the upstream of Brantas sub watershed beginning from Sumber Brantas until the location of Automatic Water Level Recorder (AWLR) in Pendem Bridge-Batu City; 3) data which are used are assumed homogeny and the analysis is carried out due to the physical data of watershed by using the rainfall data from rainfall station in Batu city; 4) effective rainfall is analysed by using Φ-index and it is assumed equally at all of the watershed; 5) the parameters which are studied are as the hydrograph parameters; 6) parameters which are studied on Nakayasu synthetic unit hydrograph are hydrograph parameter (α) and rainfall time lag (Tg); 7) the condition of river flow (which is related to the observed hydrograph) is determined when the middle of rainy season such as estimated between December until May (the next year); 8) the separation of direct run-off hydrograph from base flow is used straight line method and observed unit hydrograph is differentiated from discharge hydrograph by using Collins method; 9) to make the limb curve and recession line hydrograph use the time to peak of observed hydrograph. Watershed is assumed as linear system which is time invariant, so the input every time will cause the same run-off [VIESSMAN *et al.* 1977].

Based on the problem as describe as above, this study intends as follow: 1) to analyse the difference of α and Tg parameters between which is recommended by Nakayasu and in the study location of watershed; 2) to know the influence of river characteristic to the α parameter due to the observed hydrograph; 3) to know the influence of main river length which is used in Nakayasu and Limantara synthetic unit hydrograph to the time concentration; 4) to analyse the deviation of Nakayasu and Limantara synthetic unit hydrograph to the observed hydrograph; and 5) to know the synthetic unit hydrograph which is suitable for the upstream Brantas sub watershed.

MATERIALS AND METHODS

STUDY LOCATION

Study location is in the upstream of Brantas sub watershed. Geographically, it is located at the east longest of 122°17’10,90” until 122°57’00,00” and south longest of 7°44’55,1” until 8°26’35,45” with the outlet on the Automatic Water Level Recorder (AWLR) of Pendem Bridge-Batu City, East Java Province of Indonesia. Area of the sub watershed is 152.232 km^2. Study location in the upstream of Brantas sub watershed is beginning from Sumber Brantas until the station of Automatic Water Level Recorder (AWLR) of Pendem Bridge-Batu City. Location of the study area is as in Figure 1.

DATA COLLECTING

Data which are needed in this study are as follow:

1) map of watershed with the minimum scale of 1:25.000;
2) discharge data from the station of Automatic Water Level Recorder (AWLR) included the discharge curve there;
3) hourly rainfall from Automatic Rainfall Recorder (ARR) and daily rainfall from manual station if there does not have ARR.

ANALYSIS OF DATA

The steps of data analysis are as follow:

1) to transform the stage hydrograph into discharge hydrograph (rating curve) at AWLR station of Pendem Bridge and it is formulated as follow:

$$Q = 5.551\,(H - 588.360)^2 \qquad (1)$$

where: H = water level, cm;

2) river section is assumed not changed; river slope is influenced the flow velocity and functional in forming hydrograph; the river slope (S) in upstream of Brantas subwatershed is 0.0394;

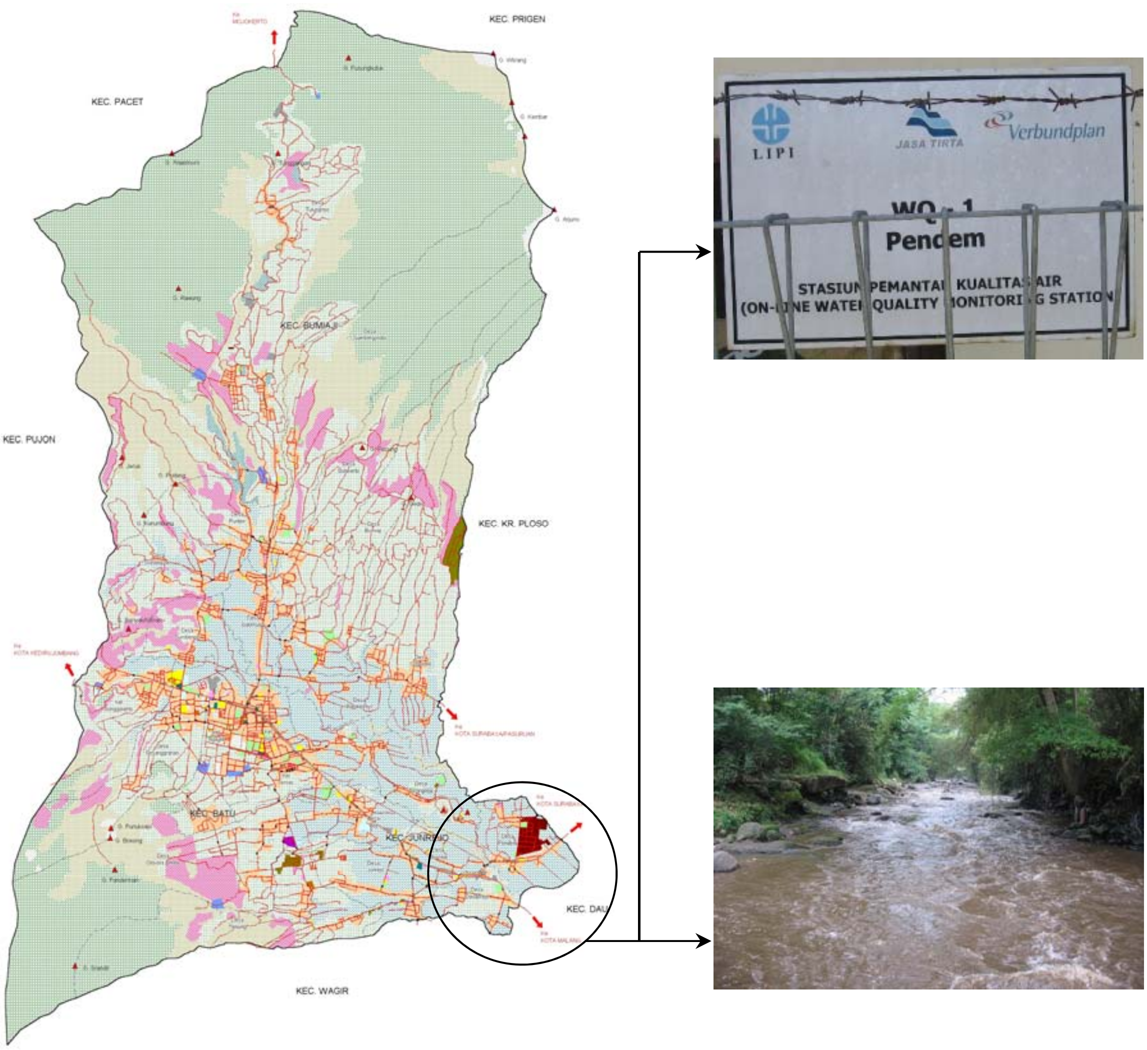


Fig. 1. Location of the study area; source: Department of Technological Study and Application, Indonesia [BPPT 2013]

3) roughness coefficient (n) of watershed is estimated based on the formula as follow [LIMANTARA 2010a]:

$$n = 0.035\ (1 + \frac{A_f}{A}) \quad (2)$$

where: n = roughness coefficient of watershed; A_f = area of forest; A = area of watershed; roughness coefficient (n) at upstream Brantas sub watershed is 0.0503;
4) base flow – the separation of base flow from hydrograph is necessary for obtaining the direct run-off hydrograph; in this study is selected the straight line method;
5) water losses; type of water losses includes interception, evaporation, basin storage, and the biggest losses is infiltration; in this study, it is used Phi-index which is constant during the rainy; phi-index is one of the methods for analysing infiltration due to the relation between rainfall and run-off in small watershed;
6) differentiation of unit hydrograph; unit hydrograph of watershed can be differentiated from observed flood hydrograph which is produced by effective rainfall with equally distribution; the differentiation of unit hydrograph in this study uses Collins method [LIMANTARA 2010a,b].

Observed unit hydrograph

Observed unit hydrograph is as a hydrograph that illustrates a series of rainfall which only produces the effective rainfall in a unit of time and it can be differentiated from separated rainfall with equally intensity or single period rainfall and it is very rarely happened, however complex period rainfall is very often happened [VIESSMAN *et al.* 1977]. Numerical analysis is used for differentiating the observed unit hydrograph, one of them is Collins method. The steps in using Collins method is summarized as follow [CORDERY 1991]:
1) to prepare the direct run-off hydrograph;
2) to prepare the effective rainfall and separating the maximum one;
3) to analyse the volume of direct run-off;
4) to try the first ordinate of unit hydrograph regarding to the direct run-off;
5) to analyse the multiplication of effective rainfall (except the maximum rainfall) and the trial ordinate of hydrograph ($\Sigma Re \cdot U$), Re = maximum effective rainfall, U = ordinate of hydrograph;
6) to analyse the calibration factor (F) for the next step, F = calibration factor;
7) to analyse the ordinate of estimation unit hydrograph;
8) to analyse the ordinate deviation at the beginning of trial due to the ordinate on the previous step and then it is carried out the return process until there is obtained the smallest deviation;
9) based on the observed unit hydrograph analysis, then there is measured the size of Q_p, T_p, and T_b and it is found the average, Q_p = peak discharge, T_p = time to peak and T_b = time base.

On the complex rainfall (non single rainfall), the differentiation should be carried out with the Collins method for avoiding the error streak [VIESSMAN *et al.* 1977].

Synthetic unit hydrograph (SUH)

In this study, the analysis of synthetic unit hydrograph peak discharge uses the method of Nakayasu and Limantara synthetic unit hydrograph.

Synthetic unit hydrograph of Nakayasu

Nakayasu from Japan has observed the unit hydrograph at some rivers in Japan. Nakayasu has made the formula of synthetic unit hydrograph as follow [VIESSMAN *et al.* 1977]:

$$Q_p = \frac{CA \cdot R_0}{3.6(0.3T_p + T_{0.3})} \quad (3)$$

where: Q_p = peak discharge, $m^3 \cdot s^{-1}$; CA = catchment area, km^2; R_0 = unit rainfall, 1 mm; T_p = time from the rainfall beginning until flood peak, hour; $T_{0.3}$ = needed time for discharge decreasing from peak discharge until 30% of peak discharge, hour.

To calculate T_p and $T_{0.3}$ is used the formula as follow:

$$T_p = T_g + 0.8T_r \quad (4)$$

$$T_{0.3} = \alpha \cdot T_g \quad (5)$$

$$T_r = 0.75Tg \quad (6)$$

where:

a) if the river length >15 km:

$$T_g = 0.4 + 0.058L$$

b) if the river length <15 km:

$$T_g = 0.21L^{0.7}$$

where: T_g = time lag, hour; T_r = time unit of rainfall, hour; α = parameter of hydrograph; L = length of main river, km.

Figure 2 presents the sketch of Nakayasu synthetic unit hydrograph.

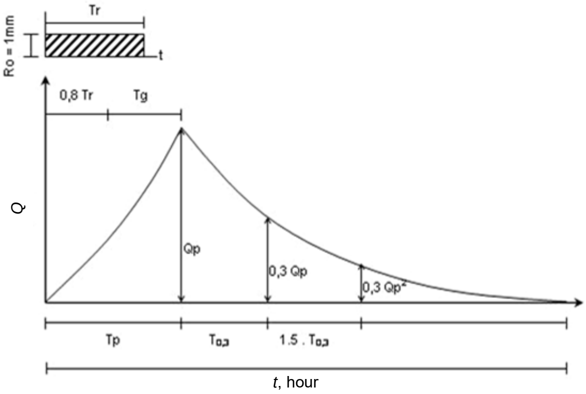


Fig. 2. Sketch of Nakayasu synthetic unit hydrograph; source: LIMANTARA [2010b]

Limb curve of Nakayasu synthetic unit hydrograph has the formula as follow:
1) time to peak: $0 \le t < T_p$

$$Q_n = Q_p \left(\frac{t}{T_p} \right)^{2.4} \quad (7)$$

2) time recession:

$T_p \le t < (T_p + T_{0.3})$:

$$Q_t = Q_p \cdot 0.3^{\frac{t - T_p}{T_{0.3}}} \quad (8)$$

$(T_p + T_{0.3}) \le t < (T_p + T_{0.3} + 1.5T_{0.3})$

$$Q_t = Q_p \cdot 0.3^{\frac{t - T_p + 0.5T_{0.3}}{1.5 - T_{0.3}}} \quad (9)$$

$t > (T_p + T_{0.3} + 1.5T_{0.3})$:

$$Q_t = Q_p \cdot 0.3^{\frac{t - T_p + 1.5T_{0.3}}{2T_{0.3}}} \quad (10)$$

Synthetic unit hydrograph of Limantara

Physical parameter of watershed. There are 5 parameters of watershed which are used in synthetic unit hydrograph of Limantara as follow [LIMANTARA 2009a]: 1) area of watershed (*A*); 2) length of main river (*L*); 3) length of river that is measured until the close point to the weight point of watershed (*Lc*); 4) slope of river (*S*); and 5) coefficient of roughness (*n*).

Formula of Limantara synthetic unit hydrograph (of peak discharge) [LIMANTARA 2009a]:

$$Q_p = 0.042\, A^{0.451}\, L^{0.497}\, Lc^{0.356}\, S^{-0.131}\, n^{0.168} \quad (11)$$

where: Q_p = flood peak discharge of unit hydrograph, $m^3 \cdot s^{-1} \cdot mm^{-1}$; A = area of watershed, km^2; L = length of main river, km; Lc = length of river that is measured until the close point to the weight point of watershed, km; S = slope of main river; n = roughness coefficient of watershed; 0.042 = coefficient of unit conversion, $m^{0.25} \cdot s^{-1}$.

Formula of limb curve [LIMANTARA 2009a]:

$$Q_n = Q_p \cdot (t/T_p)^{1.107} \quad (12)$$

where: Q_n = discharge on the limb curve equation, $m^3 \cdot s^{-1} \cdot mm^{-1}$; Q_p = peak discharge of unit hydrograph, $m^3 \cdot s^{-1} \cdot mm^{-1}$; t = time of hydrograph, hour; T_p = time to peak of hydrograph, hour.

Formula of recession line [LIMANTARA 2009a]:

$$Q_t = Q_p \cdot 10^{0.175(Tp - t)} \quad (13)$$

where: Q_t = discharge on the recession curve equation, $m^3 \cdot s^{-1} \cdot mm^{-1}$; Q_p = peak discharge of unit hydrograph, $m^3 \cdot s^{-1} \cdot mm^{-1}$; T_p = time to peak of hydrograph, hour; t = time of hydrograph, hour; 0.175 = coefficient of unit conversion, s^{-1}.

Estimation of time to peak (T_p). To estimate time to peak (T_p) can be used the formula as in Nakayasu synthetic unit hydrograph.

Enforceability limitation of Limantara synthetic unit hydrograph. Synthetic unit hydrograph of Limantara can be applied in the other watershed which has the similarity of characteristic with the watersheds in research location. The technical specification of Limantara synthetic unit hydrograph is presented as in Table 1.

Table 1. Technical specification of Limantara synthetic unit hydrograph

Parameter	Unit	Range
Area of watershed A	km^2	0.325–1,667.500
Length of main river L	km	1.16–62.48
The distance from weight point of watershed to outlet L_c	km	0.50–29.386
Slope of main river S	–	0.00040–0.14700
Roughness coefficient of watershed N	–	0.035–0.070
Area weight of forest A_f	%	0.00–100.00

Source: LIMANTARA [2009a], modified.

RESULTS AND DISCUSSION

ANALYSIS OF OBSERVED UNIT HYDROGRAPH

Unit hydrograph which was analysed for every flood case had not been as representative unit hydrograph of the watershed. Therefore, it was needed a unit hydrograph that was differentiated from 9 flood cases and then they were averaged to produce representative unit hydrograph of the watersheds. The data is presented as in Table 2.

The best original data is come from the different rainfall duration and peak discharge, so the obtained

Table 2. Data of flood hydrograph in upstream Brantas watershed

Event number	Q ($m^3 \cdot s^{-1}$) on								
	08.02.1993	27.02.1995	29.11.1995	21.02.1996	15.02.1996	02.10.1996	14.12.1997	31.01.1998	05.03.1998
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	42.00	11.00	12.00	41.00	36.00	26.00	17.00	1.00	33.00
3	47.00	28.00	24.00	38.00	33.00	37.00	15.00	7.00	38.00
4	43.00	48.00	24.00	27.00	60.00	51.00	10.00	7.00	43.00
5	38.00	46.00	63.00	19.00	77.00	49.00	6.00	11.00	32.00
6	31.00	37.00	42.00	12.00	61.00	39.00	4.00	32.00	27.00
7	15.00	32.00	37.00	8.00	38.00	32.00	3.00	44.00	26.00
8	12.00	28.00	29.00	6.00	32.00	26.00	2.00	45.00	22.00
9	6.00	23.00	29.00	5.00	27.00	21.00	1.00	44.00	19.00
10	4.00	18.00	16.00	4.00	25.00	18.00	0.00	36.00	15.00
11	3.00	14.00	11.00	4.00	22.00	16.00	0.00	27.00	13.00
12	2.00	10.00	11.00	4.00	19.00	14.00	0.00	22.00	10.00
13	0.00	9.00	4.00	3.00	16.00	12.00	0.00	17.00	8.00
14	0.00	7.00	3.00	2.00	13.00	11.00	0.00	13.00	7.00
15	0.00	5.00	3.00	1.00	9.00	10.00	0.00	11.00	5.00
16	0.00	3.00	1.00	1.00	7.00	9.00	0.00	8.00	4.00
17	0.00	2.00	0.00	0.00	6.00	6.00	0.00	6.00	3.00
18	0.00	1.00	0.00	0.00	0.00	5.00	0.00	4.00	1.00
19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00

Source: Department of Technological Study and Application, Indonesia [BPPT 2013].

unit hydrograph has to be changed into dimensionless unit hydrograph ordinate. Based on the dimensionless unit hydrograph, the values of peak discharge (Q_p) and time to peak (T_p) will be the same. Then, the values of time base has to be equated formerly. Table 3 presents the coordinates of observed unit hydrograph.

Table 3. Coordinate of observed unit hydrograph

t/Tp_{mean}	Q/Qp_{mean}	t, hour	Q, $m^3 \cdot s^{-1} \cdot mm^{-1}$
0.00	0.00	0.00	0.000
0.33	0.36	1.00	2.900
0.67	0.79	2.00	6.397
1.00	**1.00**	**3.00**	**8.050**
1.33	0.88	4.00	7.121
1.67	0.68	5.00	5.472
2.00	0.51	6.00	4.128
2.33	0.38	7.00	3.067
2.67	0.28	8.00	2.245
3.00	0.25	9.00	1.973
3.33	0.17	10.00	1.399
3.67	0.12	11.00	0.933
4.00	0.11	12.00	0.647

Explanations: Tp_{mean} = average time from the rainfall beginning until flood peak, Q = water discharge, Qp_{mean} = average peak discharge, t = time.
Source: own study.

Synthetic unit hydrograph of Nakayasu (Nakayasu SUH)

To analyse the synthetic unit hydrograph of Nakayasu, there is used the formula number 3 until 9 as above by entering the physical parameter data of watershed such as length of main river and area of watershed.

Parameter Nakayasu synthetic unit hydrograph before calibration. The different parameter in each method will give the different result. Before there is carried out calibration, some value of α parameter have produced the different unit hydrograph peak discharge. The result shows as in Table 4 and Figure 3.

Based on the analysis of some α (before calibration) by using Nakayasu method, there is obtained the

Table 4. Some value of α, time to peak, and peak discharge of synthetic unit hydrograph of Nakayasu (Nakayasu SUH) in sub watershed of Upstream Brantas

α value	Tp hour	Qp	QpCollins	Deviation %	(Qp – QpCollins)^2
		$m^3 \cdot s^{-1} \cdot mm^{-1}$			
1.800	2.630	10.358	8.050	22.28	5.33
1.900	2.630	9.913	8.050	18.79	3.47
2.000	2.630	9.506	8.050	15.31	2.12
2.100	2.630	9.130	8.050	11.82	1,17
2.200	2.630	8.783	8.050	8.34	0.54
2.300	2.630	8.461	8.050	4.86	0.17
2.400	**2.630**	**8.163**	**8.050**	**1.37**	0.01
2.500	2.630	7.884	8.050	2.07	0.03
				$\sum(Qp - Qp\text{Collins})^2$	12.84

Root Mean Square Error (RMSE) acc. to RITTER and CARPENA [2013] = $(12.84/N)^{1/2} = (12.84/8)^{1/2} = 1.27$.
Explanations: N = number of data, Tp = time to peak, Qp = peak discharge, Qp_{max} = maximum peak discharge, QpCollins = peak discharge regarding to Collins method.
Source: own study.

suitable α is 2.400 with the smallest deviation of 1.373% and the RMSE is 1.27. Table 5 and Figure 4 present the comparison between observed unit hydrograph (HSO) by Collins method and Nakayasu SUH.

Parameter of Nakayasu SUH after calibration

Calibration of Nakayasu SUH in this study is only carried out for the α parameter and Tg (time lag). The calibration is carried out by trial of α parameter and λ at the equation of Tg so it is obtained the time to peak and peak discharge with the smallest deviation to the observed unit hydrograph (<10%).

Based on the Nakayasu SUH method, the formula of Tg is as follow: $Tg = 0.4 + 0.058L$ for L >15 km and $Tg = 0.21L^{0.7}$ for L <15 km, however, for calibration in this study, the formula is modified into $Tg = 0.4 + 0.058L^{\lambda}$, with the value of λ is as the result of trial.

Table 6 presents the trial of α and λ parameter and Table 7 presents some value of α, time to peak, and peak discharge of Nakayasu SUH and Figure 5 presents the comparison between Nakayasu SUH with some α parameter and HSO (observed unit hydrograph).

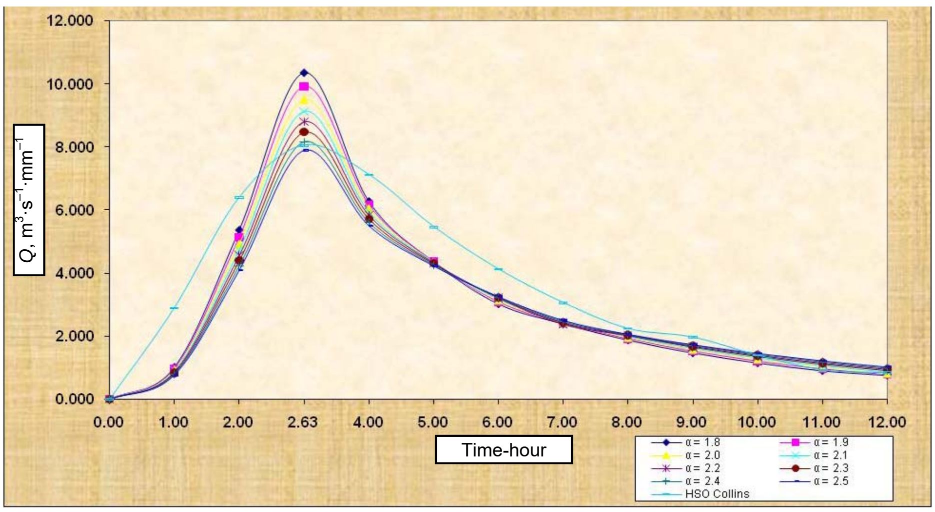


Fig. 3. Synthetic unit hydrograph of Nakayasu (Nakayasu SUH) due to the some value of α; source: own study

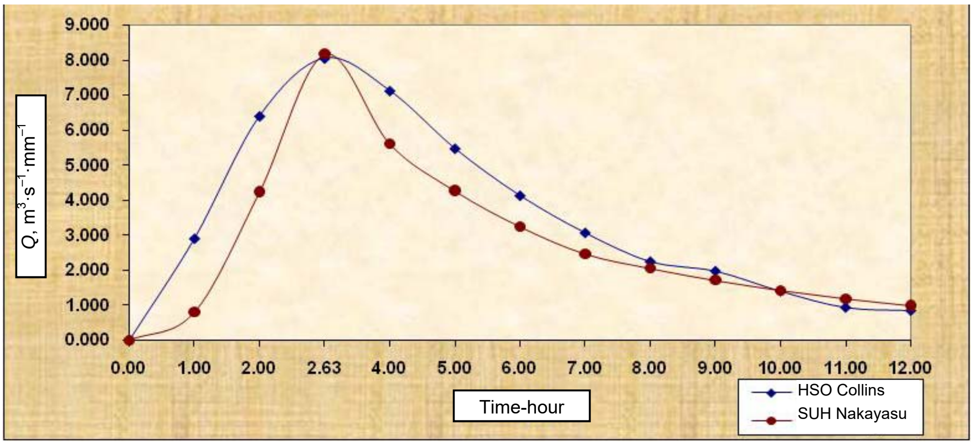


Fig. 4. Observed unit hyrograph (HSO) of Collins method and synthetic unit hydrograph of Nakayasu (Nakayasu SUH) with $\alpha = 2.400$; source: own study

Table 5. Comparison between observed unit hydrograph (HSO) by Collins method and synthetic unit hydrograph of Nakayasu (Nakayasu SUH)

No.	Time *t* hour	Collins HSO	Nakayasu SUH	Deviation %	(*Qp*Collins – QpNakayasu)^2
		$m^3 \cdot s^{-1} \cdot mm^{-1}$			
0	0.00	0.000	0.000	0.00	0.00
1	1.00	2.900	0.802	72.36	4.40
2	2.00	6.397	4.231	33.87	4.69
3	**2.63**	**8.050**	**8.163**	**1.37**	**0.01**
4	4.00	7.121	5.606	21.27	2.30
5	5.00	5.472	4.262	22.12	1.46
6	6.00	4.128	3.240	21.51	0.79
7	7.00	3.067	2.463	19.67	0.37
8	8.00	2.245	2.048	8.79	0.04
9	9.00	1.973	1.706	13.53	0.07
10	10.00	1.399	1.421	1.56	0.00
11	11.00	0.933	1.184	21.13	0.06
12	12.00	0.847	0.986	14.12	0.02
				∑(*Qp*Collins – *Qp*Nakayasu)^2	14.21

Root Mean Square Error (*RMSE*) acc. to RITTER and CARPENA [2013] = $(14.21/N)^{1/2} = (14.21/12^{1/2} = 1.09$.
Explanations: N = number of data, *Qp* = peak discharge.
Source: own study.

Table 6. Trial on parameter value of α and λ for synthetic unit hydrograph of Nakayasu (Nakayasu SUH) in subwatershed of Upstream Brantas

α value	λ value	Time to peak (*Tp*) hour	Peak discharge (*Qp*) $m^3 \cdot s^{-1} \cdot mm^{-1}$
1.800	1.072	3.000	8.702
1.900	1.072	3.000	8.325
1.979	1.072	3.000	8.051
2.100	1.072	3.000	7.661
2.200	1.072	3.000	7.368
2.300	1.072	3.000	7.096
2.400	1.072	3.000	6.843
2.500	1.072	3.000	6.608

Source: own study.

After calibration the suitable α parameter in upstream Brantas sub watershed is 1.979 with the smallest deviation of 0.001% and the *RMSE* is 0.84. Table 8 and Figure 6 present the comparison between HSO of Collins method and Nakayasu SUH after calibration.

Table 7. Value of some α parameter, time to peak, and peak discharge for synthetic unit hydrograph of Nakayasu (Nakayasu SUH) in sub watershed of Upstream Brantas

α value	*Tp* hour	*Qp*	*Qp*Collins	Deviation %	(*Qp* – *Qp*Collins)^2
		$m^3 \cdot s^{-1} \cdot mm^{-1}$			
1.800	3.000	8.702	8.050	7.48	0.43
1.900	3.000	8.325	8.050	3.29	0.08
1.979	3.000	8.051	8.051	0.00	0.00
2.100	3.000	7.661	8.050	4.84	0.15
2.200	3.000	7.368	8.060	8.48	0.48
2.300	3.000	7.096	8.060	11.86	0.93
2.400	3.000	6.843	8.060	15.00	1.48
2.500	3.000	6.608	8.060	17.92	2.11
				∑(*Qp* – *Qp*Collins)^2	5.66

Root Mean Square Error (RMSE) acc. to RITTER and CARPENA [2013] = $(5.66/N)^{1/2} = (5.66/8)^{1/2} = 0.84$.
Explanations: *Tp* = time to peak, *Qp* = peak discharge.
Source: own study.

Table 8. The comparison between observed unit hydrograph (HSO) of Collins method and synthetic unit hydrograph of Nakayasu (Nakayasu SUH) after calibration

No	Time *t* hour	Collins HSO	Nakayasu SUH	Deviation %	(*Qp*Collins – *Qp*Nakayasu)^2
		$m^3 \cdot s^{-1} \cdot mm^{-1}$			
0	0.00	0.000	0.000	0.00	0.00
1	1.00	2.900	0.576	80.12	5.40
2	2.00	6.397	3.042	52.44	11.46
3	**3.00**	**8.050**	**8.051**	**0.00**	**0.00**
4	4.00	7.121	6.105	14.27	1.03
5	5.00	5.472	4.630	15.40	0.71
6	6.00	4.128	3.511	14.95	0.38
7	7.00	3.067	2.663	13.17	0.16
8	8.00	2.245	2.143	4.53	0.01
9	9.00	1.973	1.782	9.64	0.04
10	10.00	1.399	1.482	5.64	0.01
11	11.00	0.933	1.233	24.38	0.09
12	12.00	0.847	1.025	17.41	0.03
				∑(*Qp*Collins – *Qp*Nakayasu)^2	19.32

Root Mean Square Error/RMSE acc. to RITTER and CARPENA [2013] = $(19.32/N)^{1/2} = (19.32/12)^{1/2} = 1.27$.
Explanations: N = number of data; *Qp* = peak discharge.
Source: own study.

Table 9 presents the recapitulation of Nakayasu SUH parameters before and after calibration.

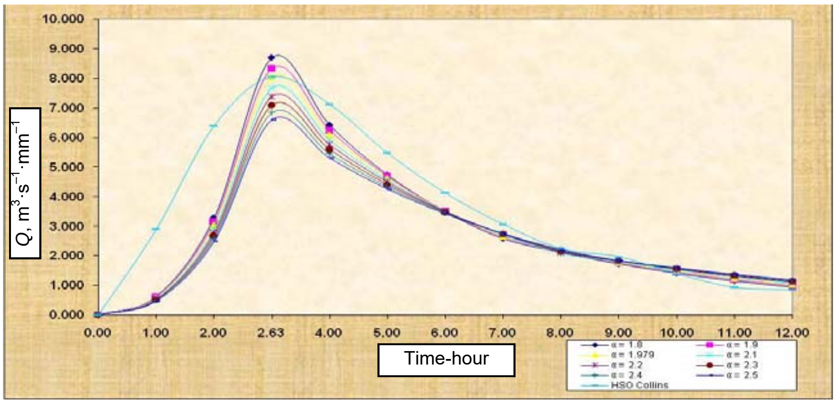


Fig. 5. Comparison between synthetic unit hydrograph of Nakayasu (Nakayasu SUH) with some α parameter and observed unit hyrograph (HSO); source: own study

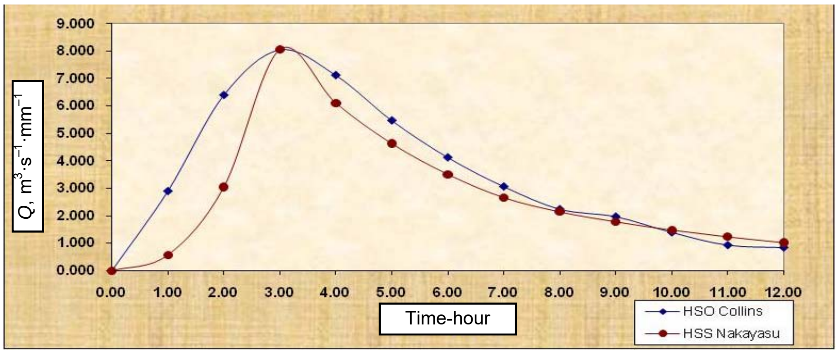


Fig. 6. Comparison between synthetic unit hydrograph of Nakayasu (Nakayasu SUH) with α = 1.979 and observed unit hyrograph (HSO); source: own study

Table 9. Parameters of synthetic unit hydrograph of Nakayasu (Nakayasu SUH) before and after calibration

Parameter	Before calibration	After calibration
α	2.500	1.979
Tg	$0.4 + 0.058L$	$0.4 + 0.058L^{1.072}$

Explanations: α = parameter of hydrograph, Tg = time lag.
Source: own study.

Synthetic unit hydrograph of Limantara (Limantara SUH)

To analyse the synthetic unit hydrograph of Nakayasu, there is used the formula number 11 until 13 as above by entering the physical parameter data of watershed regarding to the technical specification of Limantara SUH.

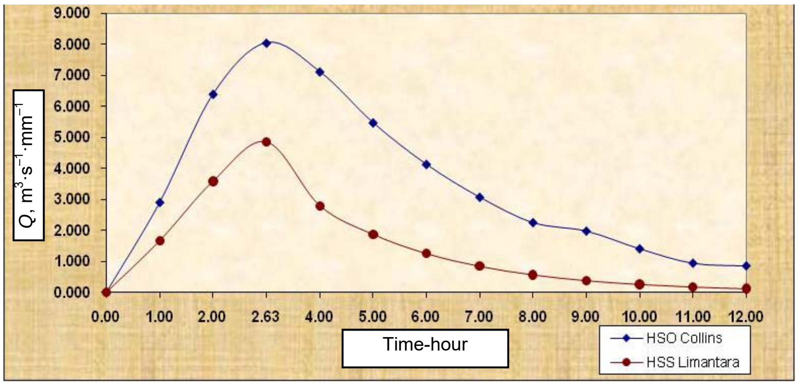
Parameter of Limantara SUH before calibration. The influenced parameters on the propagation process of Limantara SUH are area of watershed, length of the longest main river, length of river that is measured until the close point to the weight point of watershed, slope of main river, roughness coefficient of watershed, and estimation of rainfall concentration time (Tg) which each of the parameter is influenced time to peak and peak discharge. The parameter value for time to peak and peak discharge of Limantara SUH is as follow: Tp (time to peak) is 2.63 hours; Qp (peak discharge) is 4.868 $m^3 \cdot s^{-1}$; QpCollins (peak discharge regarding to the Collins method) is 8.050 $m^3 \cdot s^{-1} \cdot mm^{-1}$; and the deviation between Qp and QpCollins is 39.33%. Table 10 and Figure 7a presents the comparison of HSO Collins method and Limantara SUH before calibration.

Table 10. Comparison of observed unit hydrograph HSO-Collins method and synthetic unit hydrograph (SUH) of Limantara before calibration

No	Time t hour	Collins HSO	Limantara SUH	Deviation %	(QpCollins – QpLimantara)^2
		$m^3 \cdot s^{-1} \cdot mm^{-1}$			
0	0.00	0.000	0.000	0.00	0.00
1	1.00	2.900	1.669	42.44	1.52
2	2.00	6.397	3.595	43.80	7.85
3	**3.00**	**8.050**	**4.868**	**39.53**	**10.13**
4	4.00	7.121	2.803	60.64	18.65
5	5.00	5.472	1.873	65.77	12.95
6	6.00	4.128	1.252	69.67	8.27
7	7.00	3.067	0.837	72.71	4.97
8	8.00	2.245	0.559	75.09	2.84
9	9.00	1.973	0.374	81.05	2.56
10	10.00	1.399	0.250	82.14	1.32
11	11.00	0.933	0.167	82.11	0.59
12	12.00	0.847	0.112	86.82	0.54
$\sum$(QpCollins – QpNakayasu)^2					72.19

Root Mean Square Error ($RMSE$) acc. to RITTER and CARPENA [2013] = $(72.19/N)^{1/2} = (72.19/12)^{1/2} = 2.45$.
Explanation: HSO = observed unit hydrograph, SUH = synthetic unit hydrograph, N = number of data, Qp = peak discharge.
Source: own study.

Parameter of Limantara SUH after calibration. Regarding to the limitation of Limantara SUH, there is only rainfall time lag (Tg) that can be calibrated, however, the other parameters cannot be changed be-a)



b)

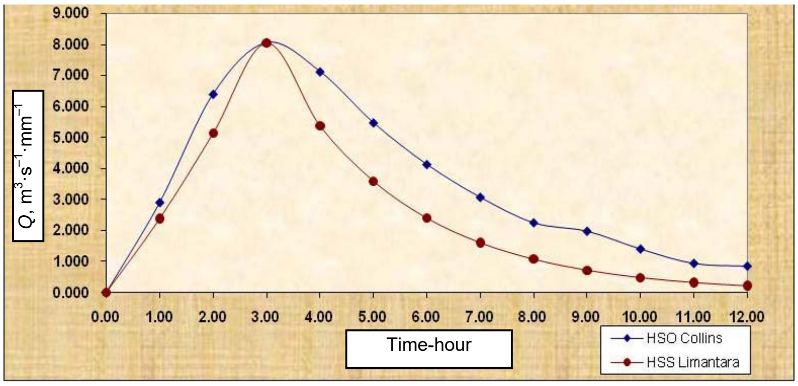


Fig. 7. Comparison between Observed Unit Hyrograph HSO of Collins (HSO-Collins) and synthetic unit hydrograph of Limantara (Limantara SUH): a) before calibration, b) after calibration; source: own study

cause there are as the remained data of the watershed itself. According to the founder [LIMANTARA 2010a,b], there is roughness coefficient of watershed can be calibrated although the calibration result is out of the recommended range. Table 11 presents the parameter value for time to peak and peak discharge of Limantara SUH. The parameter value for time to peak and peak discharge of synthetic unit hydrograph (SUH) of Limantara in sub watershed of Upstream Brantas is as follow: *Tp* (time to peak) is 3 hours; *Qp* (peak discharge) is 8.050 $m^3 \cdot s^{-1} \cdot mm^{-1}$; *Qp*Collins (peak discharge regarding to the Collins method) is 8.050 $m^3 \cdot s^{-1} \cdot mm^{-1}$; and the deviation between *Qp* and *Qp*Collins is 0%. Figure 7b presents the comparison of HSO-Collins method and Limantara SUH after calibration. Table 12 presents the parameter recapitulation of Limantara SUH before and after calibration.

Table 11. Comparison of observed unit hydrograph HSO of Collins (HSO-Collins) method and synthetic unit hydrograph of Limantara (Limantara SUH) after calibration

Time *t* Hour	Collins-HSO	Limantara SUH	Deviation %	(*Qp*Collins – *Qp*Limantara)^2
	$m^3 \cdot s^{-1} \cdot mm^{-1}$			
0.00	0.000	0.000	0.00	0.00
1.00	2.900	2.386	17.72	0.27
2.00	6.397	5.139	19.67	1.58
3.00	**8.050**	**8.050**	**0.00**	**0.00**
4.00	7.121	5.380	24.44	3.03
5.00	5.472	3.596	34.29	3.52
6.00	4.128	2.403	41.79	2.98
7.00	3.067	1.606	47.62	2.14
8.00	2.245	1.073	52.19	1.37
9.00	1.973	0.717	63.63	1.58
10.00	1.399	0.480	65.72	0.85
11.00	0.933	0.320	65.67	0.38
12.00	0.847	0.214	74.70	0.40
			∑(*Qp*Collins – *Qp*Nakayasu)^2	18.10

Root Mean Square Error (*RMSE*) acc. to RITTER and CARPENA [2013] = $(18.1/N)^{1/2} = (18.1/12)^{1/2} = 1.23$.
Explanation: HSO = observed unit hydrograph, SUH = synthetic unit hydrograph, *Qp* = peak discharge.
Source: own study.

Table 12. Parameters of synthetic unit hydrograph of Limantara (Limantara SUH) before and after calibration

Parameter	Before calibration	After calibration
Tg	$0.4 + 0.058L$	$0.4 + 0.058L^{1.072}$
L	$L^{0.497}$	$L^{0.654}$

Explanations: *Tg* = time lag, *L* = length of main river.
Source: own study.

Comparison of synthetic unit hydrograph

The difference of parameter on each method will give the different result too. Table 13 and Figure 8a presents the hydrograph ordinates of Nakayasu and Limantara SUH before calibration, and Collins-HSO. However, Table 13 and Figure 8b presents the hydrograph ordinates of Nakayasu and Limantara SUH after calibration, and Collins-HSO.

The study is conducted in upstream Brantas sb watershed. Result shows that there is no significantly difference between *α* parameter that is recommended by Nakayasu and by using dimensionless unit hydrograph. The *α* parameter due to the calibration result is

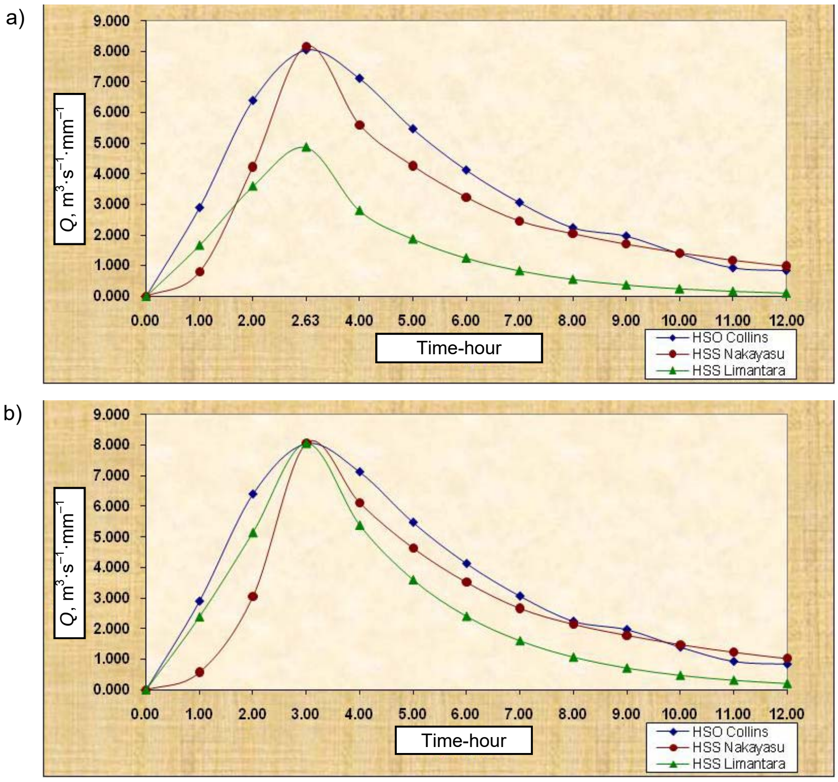


Fig. 8. Comparison of Observed Unit Hyrograph HSO of Collins (HSO-Collins), Synthetic Unit Hydrograph (SUH) of Nakayasu and Limantara; a) before calibration, b) after calibration; source: own study

Table 13. Comparison of observed unit hydrograph HSO of Collins (HSO-Collins), of synthetic unit hydrograph (SUH) of Nakayasu and Limantara before and after calibration

No	Time *t* hour	HSO of Collins	Nakayasu SUH	Limantara SUH
		$m^3 \cdot s^{-1} \cdot mm^{-1}$		
Before calibration				
0	0.00	0.000	0.000	0.000
1	1.00	2.900	0.802	1.669
2	2.00	6.397	4.231	3.595
3	**2.63**	**8.050**	**8.163**	**4.868**
4	4.00	7.121	5.606	2.803
5	5.00	5.472	4.262	1.873
6	6.00	4.128	3.240	1.252
7	7.00	3.067	2.463	0.837
8	8.00	2.245	2.048	0.559
9	9.00	1.973	1.706	0.374
10	10.00	1.399	1.421	0.250
11	11.00	0.933	1.184	0.167
12	12.00	0.847	0.986	0.112
After calibration				
0	0.00	0.000	0.000	0.00
1	1.00	2.900	0.576	2.386
2	2.00	6.397	3.042	5.139
3	**3.00**	**8.050**	**8.050**	**8.050**
4	4.00	7.121	6.105	5.380
5	5.00	5.472	4.650	3.596
6	6.00	4.128	3.511	2.403
7	7.00	3.067	2.663	1.606
8	8.00	2.245	2.143	1.073
9	9.00	1.973	1.782	0.717
10	10.00	1.399	1.482	0.480
11	11.00	0.933	1.233	0.320
12	12.00	0.847	1.025	0.214

Explanation: HSO = observed unit hydrograph, SUH = synthetic unit hydrograph.
Source: own study.

1.979 and the formula of Tg is modified from $Tg = 0.4 + 0.058L$ becomes as $Tg = 0.4 + 0.058L^{1.072}$ Analysis of deviation for finding the value of α by using Nakayasu dimensionless SUH indicates that α is very influenced by the characteristic factor of river. It is seen that every watershed with the certain rainfall will produce the certain value of α. Therefore, the value of α can be used for the subwatershed that has the similarity of river characteristic with the watershed which the α value is found.

The concentration time Tg of Nakayasu and Limantara SUH for upstream Brantas watershed has been modified as $Tg = 0.4 + 0.058L^{1.072}$ and it produces the result with the smallest deviation to the observed unit hydrograph (HSO). Nakayasu SUH before calibration has the parameter α = 2.400 and Tg = 1.830 with the peak discharge deviation of 1.373% and the *RMSE* is 1.27. However, after calibration, the value of parameter α = 1.979 and Tg = 2.200 with the peak discharge deviation of 0.001^{-3}% and the *RMSE* is 0.84. Limantara SUH before calibration has the parameter Tg = 1.830 with the peak discharge deviation of 39.527% and the *RMSE* is 2.45 and after calibration, it has the parameter Tg = 2.200 with the peak discharge deviation of 2.10^{-4}% and the *RMSE* is 0.23.

CONCLUSIONS

1. Result shows that there is no significantly difference between α parameter that is recommended by Nakayasu and by using dimensionless unit hydrograph.

2. Parameter α is very influenced by the characteristic factor of river. It is seen that every watershed with the certain rainfall will produce the certain value of α.

3. Based on the analysis result of Nakayasu and Limantara SUH, the suitable method for upstream Brantas watershed is Limantara SUH which has the peak discharge deviation of 2.10^{-4}% due to the Collins-observed unit hydrograph.

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Dwi PRIYANTORO, Lily M. LIMANTARA

Ocena zgodności syntetycznego hydrogramu jednostkowego
(przypadek górnej części zlewni cząstkowej Brantas, Prowincja Wschodniej Jawy, Indonezja)

STRESZCZENIE

Celem badań była analiza hydrogramu dla górnej części zlewni cząstkowej Brantas. Porównano hydrogram uzyskany metodą syntetycznego hydrogramu jednostkowego wg Nakayasu, syntetycznego hydrogramu jednostkowego wg Limantary i obserwowanego hydrogramu jednostkowego. Badania zmierzały przede wszystkim do poznania różnic wartości parametrów hydrogramu: α i *Tg* zalecanych przez Nakayasu i mierzonych na obszarze badań, poznania wpływu długości rzeki (używanego w metodach Nakayasu i Limantary) na czas koncentracji oraz określenie odchyleń rzędnej hydrogramu między metodą Nakayasu i Limantary w powiązaniu z obserwowanym hydrogramem. Oczekiwano, że wyniki dadzą podstawy do zalecenia hydrogramu odpowiedniego dla górnej części zlewni Brantas, by mógł on być stosowany do przyszłego planowania struktury zasobów wodnych.

Słowa kluczowe: *metoda Limantary, metoda Nakayasu, obserwowany hydrogram, syntetyczny hydrogram jednostkowy*