The Limiting Physical Parameter of Nakayasu Synthetic Unit Hydrograph

Dian Kamila, Lily Montarcih Limantara, Mohammad Bisri, Widandi Soetopo

Abstract- Hydro-logical approaches in the watershed systems have granted great contributions to the hydraulic structured planning. However, it is not too easy to understand the process of run off thoroughly. The important factor in the waterworks design is to know the flood which is happened and this value will determine the dimension of waterworks which is closely related with the risk and the economic value of waterworks design. The Synthetic Unit Hydrograph is a popular method that is used in many designs of waterworks mainly in analyzing the design flood of ungauged watershed. One of them that is usually used in Indonesia is the Nakayasu Synthetic Unit Hydrograph which is found based on the observation in Japan (1948). This model is depended on the corrected factor of α influential one on the ordinate and time base of unit hydrograph. This study intends to investigate the influential factors to the physical parameter of α on the Nakayasu Synthetic Unit hydrograph. The limiting physical parameters is predicted increasingly related to the morphometric factors of watershed.

Keywords: physical parameter, model, watershed

I. INTRODUCTION

The runoff distribution at the rainfall and stream behaviors due to the several approached by the engineering methods and the unit hydrograph method has been promoted for recent years. It is very difficult to understand the process of run-off thoroughly [1]. The rainfall-induced runoff process is generally given in a curve form and shows the runoff variations towards the time during a given rainfall event [2]. The unsure of hydrograph that is peak discharge and time to peak are very essential in the planning and design of flood-control systems and design of urban drainage systems [3]. Ideally, every watershed has its own particular unit hydrograph. Realizing that the Synthetic Unit Hydrograph models have been researched and developed in the areas which the watersheds are far different than the ones applied, they therefore quite often come up with inaccurate results, which affects the design of the hydro structure [4].

Sherman (1932) [5] has found the unit hydrograph which is the first method that does not only determine the peak discharge/ flow [6]. the next research is the synthetic unit hydrograph which is started by Snyder (1938) and Gray (1961) [5]. This research gives some hydrograph characteristics such as peak discharge, peak time ,and time base. However, the additional parameters that is as the characteristic of watersheds reservoirs, was pioneered by Clark, (1943) [5]. Then, in 1972, the Soil Conservation Service (SCS) obtains the dimensionless synthetic unit hydrograph and in 1940, Dr.Nakayasu from Japan promoted the synthetic unit hydrograph based on the rivers of watersheds in Japan, which until now, it widely used and known in Indonesia as a Nakayasu synthetic unit hydrograph [7].

The Nakayasu synthetic unit hydrograph is depended on the corrected factor of α that is influenced the ordinate of unit hydrograph (Up) and time base of hydrograph (Tb). The formula of time to peak in this model does not accommodate the river slope factor. Hoesein and Limantara [8] have carried out the effort to calibrate the Nakayasu synthetic unit hydrograph in the Lesti watershed. The calibration result is $0.67 < \alpha < 1.20$, and it is out of the conditional limitation of model, This study intends to predict and estimate the factors that are influenced the parameter of α in the Nakayasu synthetic unit hydrograph.

II. MATERIALS AND METHODS

The location of study is in the plain area of Indonesia that is the Goronta;o Province with the north longest of 0° 28' 17" - 0° 35' 56" and the east longest of 122° 59' 44" - 123° 05' 59" and the area of 64,79 km^2. Map of location is presented as in the Fig. 1.

Fig. 1. Map of location
Source: Subramanya [9]

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A. The factors that influence the hydrograph

The hydrograph shape as the input response of rainfall in the watershed system is influenced by two great factors that are the factors of psycho-graph and climate [9]. In general, the rising limb is controlled by the rainfall characteristic; however, the recession limb is controlled by the watershed characteristic mainly for the land using that is functioned in controlling the infiltration rate. The teo factors that influence the hydrograph is described as in the Table 1.

Table 1.The factors that influence the hydrograph

Factor of psycho-graph	Factor of climate
1. Characteristic of watershed, that includes shape, size, slope, the depth of hill, elevation, and drainage density	1. The characteristic of rainfall, includes the intensity, duration, depth, and the direction of rain moving
2. The characteristic of infiltration that includes land cover and using, geological condition, and soil type, and there is storage like lake, pond, and the other storage	2. The initial loss
3. The characteristic of stream flow: cross section, roughness, and storage capacity	3. Evapotranspiration

B. Unit Hydrograph

The unit hydrograph is a direct run-off that is caused by a volume of effective rainfall which is well distributed in the time and space [7]. The method of hydrograph is widely used for estimating the design flood. This method is relatively simple and it is easy in the application. In addition, it does not need the complex data and gives the accurate result. Fig. 2 presents the typical of unit hydrograph.

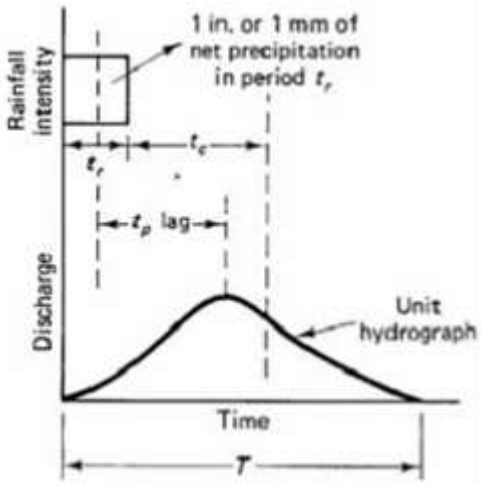

Fig. 2. The typical of unit hydrogrsph
Source: Chow [5]

C. The Synthetic Unit Hydrograph of Nakayasu

The usage of this method needs several characteristic of watershed parameters as follow [10]: a) time lag from the rainfall run-off until the peak of hydrograph; b) time lag from the weighted point of rainfall until the weighted point of hydrograph; c) time base of hydrograph: d) area of watershed: e) the length of main river/

Nakayasu is developed based on the some researches in Japan [7]. The formula of Nakayasu Synthetic Unit hydrograph is as follow::

$$QP = \frac{CA \,.R_0}{3{,}6\ (0{,}3\ TP+T_{0,3})} \quad (1)$$

Where:

QP = flood peak discharge (m^3/s/mm)

R_0 = unit rainfall (mm)

TP = time lag from the beginning of rainfall until the flood peak (hour)

$T_{0,3}$ = duration time that is needed by the discharge decreasing until 30% of flood peak (hour)

CA = watershed area until outlet (km^2)

To determine Tp and $T_{0,3}$, it is used the formula as follow::

Tp = tg + 0,8 tr

$T_{0,3}$ = α tg

Tr = 0,5 tg until tg

tg is calculated based on the condition as follow:

- If the river length: L > 15 km : tg = 0,4 + 0,058 L
- If the river length: L < 15 km : tg = 0,21 $L^{0,7}$

However, $T_{0,3}$ is determined based on the condition as follow:

α = 2 → general flow area

α = 1,5 → on the slow rising limb and fast recession limb of hydrograph

α = 3 → on the fast rising limb and slow recession limb of hydrograph

The formula of hydrograph for: 0 < t < Tp

$$Qa = (\frac{t}{Tp})^{2,4} \quad (2)$$

Where Qa is the run-off before reaching the peak discharge (m^3/s/mm)

Formula for the recession limb:

a. For the duration time: $0 \le t \le (Tp + T_{0,3})$

$$Qd_1 = Qp\ .0{,}3^{\frac{(t-Tp)}{T_{0,3}}} \quad (3)$$

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b. For the duration time: (Tp +$T_{0,3}$) ≤ t ≤ (Tp +$T_{0,3}$ + 1,5 $T_{0,3}$)

$$Qd_2 = Qp \,.\, 0{,}3^{\frac{(t-Tp+0{,}5\,T_{0,3})}{1{,}5\,.\,T_{0,3}}} \quad (4)$$

c. For the duration time: t > (Tp +$T_{0,3}$ + 1,5 $T_{0,3}$)

$$Qd_3 = Qp \,.\, 0{,}3^{\frac{(t-Tp+1{,}5\,T_{0,3})}{2\,.\,T_{0,3}}} \quad (5)$$

Volume:

$$V = (Q_t + Q_{t+1}).(T_{t+1} - T_t).0{,}5\,.\,3600 \quad (6)$$

D. The Morphometric of Watershed

Morphometric is defined as the size and mathematical analysis of configuration, shape, and dimension of earth [11]. The morphometric of watershed is as the quantitative size of watershed characteristic that is related with the geomorphology of an area. The watershed characteristic consists of watershed area, watershed shape, river network, drainage pattern and density, and river steepness gradient. The characteristic is related with the drainage process of rainfall that is drop in the watershed and influencing the outflow in the outlet (hydrograph). The morphometric of watershed analyses has the important role in understanding the relation among the watershed parameters.

D.1. The Shape and Area of Watershed

There is the various of watershed shape. It is depended on the topography and geomorphology of the watershed. However, in general, the watershed shape can be expressed by the other shape parameter that is the elongation ratio, circularity ratio, basin shape, and form factor. Watershed shape influences the flow traveling time from the watershed end until outlet [9] which has the implication to the hydrograph shape.

The form factor is defined as the ration between watershed area (A) and the quadratic of watershed length (L). The value of form factor is always less than 0.754, where the value of 0.754 is as the form factor of the perfect round watershed shape [11]. The getting smaller of form factor value, the watershed shape is getting longer. Watershed with high form factor, has the short time to peak and high peak discharge.

Watershed size is one of the important factors in building the discharge hydrograph. If the watershed area gets bigger, there is the tendency that the rainfall that is accepted is getting more [12]. Therefore, the bid watershed will produce bigger peak discharge (Qp) and time base (Tb) than the small one and it is needed the lonfer time for reaching the time to peak of hydrograph (Tp).

D.2. The length of river

The length of river is as the length of main river from upstream until outlet. Generally, the typology of river from upstream to downstream has the meander pattern and it is depended on the typology of shape and slope.

D.3. The Slope of Watershed and River

The slope of watershed and river ia directly related with the topography shape, gradient length, and river length. However, the river slope (as well as the watershed slope) gives the direct impact to the river flow velocity.

III. RESULTS AND DISCUSSION

Snyder said that the watershed factor, watershed shape, topography, river slope, river network density, and river stream are influencing the hydrograph shape. Meanwhile, Clark said that the hydrograph shape is increasingly influenced by the storage characteristic of a watershed as being expressed by Nash. In addition, it is influenced by the other morphometric factors as to be said by Snyder. It means that the factors are as the dominant factor that influences the hydrograph shape as to be said by Subramanya [9]. However, the characteristic of hydrograph shape that is as the base of unit hydrograph is as follow: 1) Hydrograph illustrates the whole combination of watershed physical characteristic; 2) Remembering that the watershed characteristic is invariant from one rainfall to the other one, so the hydrograph that is produced by the rainfall with the similar duration and pattern, gives the similar shape and time base too; and 3) The various rainfall characteristic has the significant effect on the hydrograph shape.

The quantitative size of watershed characteristic is expressed by the morphometric parameter that includes the linear morphometric, areal morphometric, and relief morphometric [11]. The linear morphometric includes the amount of section every order (N), the total river section of the whole order (N), the river length (L), branching ratio (RB), ratio of length river (RL), and the length of flow trajectory (L). The area morphometric is differentiated of the catchment area on every order (A), the relation of length-area, watershed shape, drainage density (D), flow frequency, and the constant of channel management (C). The last category is relief morphometric that consists of relief ratio (Rh), relative relief ®, relative basin height (y), relative basin area (x), and ruggedness member (R). According to Sri Harto [13], there are 4 main parameters of watershed morphometric that is assumed as the important role in forming flow that are catchment area (A), main stream length (L), average main stream slope (S), and drainage density (I).

A. Watershed Shape and Area

Elongation Ratio (ER) and Circularity Ratio (C) are as the circularity level of watershed shape. Circular watershed (with the same area) is more efficient to flow discharge than the elongated watershed. It is happened because the run-off on the elongated watershed is not concentrated as fast as on the widened watershed. It means that the distance between the rainfall drop and outlet on an elongated watershed is bigger that on the widened watershed [12], so it needs a longer time to reach watershed outlet. Therefore, the peak discharge of hydrograph becomes smaller. In addition, on the elongated watershed, the rainfall distribution is tend uneven and the process of rain evenly needs a longer time

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than on the widened watershed, so on the elongated watershed, the peak discharge of hydrograph is tend smaller than on the widened watershed.

Based on the Circularity Ratio (C), watershed can be classified into 3 categories as follow: circular (CRR > 0.9), oval ($0.9 \leq CR \leq 0.8$), and elongated ($CR < 0.8$). However, based on the size, watershed is differentiated into 3 that are small watershed ($A = 1$ km^2), meso scale watershed (10 km$^2 < A \leq 1{,}000$ km^2), and macro watershed ($A > 1{,}000$ km)

B. The Length of River

If the river is getting more and more meander, the length of river will be increasing. It means that the river slope is decreasing and it will give the implication to the average flow velocity in the river will also be decreasing. If the flow velocity in the river is decreasing, so time to peak of hydrograph will be longer.

C. The Slope of Watershed

If the river slope in the watershed is getting higher, so the flow velocity is also increasing and it gives the chance to the flow to sink in the land (infiltration) getting smaller, so most of the flow will become as the part of direct run-off. It means that the river slope is very influential the time to peak and peak discharge.

IV. CONCLUSION

Based on the analysis as above, it can be concluded that the physical parameters of watershed that is expressed as α in the Nakayasu Synthetic Unit Hydrograph is very influential by the shape and area of watershed, the length of river, and the slope of watershed.

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