A new synthetic unit hydrograph computation method based on the mass conservation principle

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Abstract

Synthetic unit hydrograph (SUH) methods are popular and play an important role in many water resources analyses of un-ganged watersheds. These methods are simple, requiring only an easy determination of watershed characteristics, such as catchment area and river length. In some cases, they may also include land-use characteristics and serve as useful tools to simulate runoff from watersheds undergoing land-use change. To develop a synthetic unit hydrograph, several synthetic unit hydrograph models such as HEC-HMS, Nakayasu, Snyder-Alexeyev, SCS, and GAMA-1 are commonly used in Indonesia. In this paper, a new method for computing the synthetic unit hydrograph based on mass conservation principles is presented. This mass conserving synthetic unit hydrograph calculation procedure, called the ITB SUH calculation method, has been implemented in the development of ITB-1 and ITB-2 SUH. The unit hydrographs are synthesized by using either a simple single function (ITB-1) or using two simple functions (ITB-2) combined with automatic adjustable peak discharge factors. Some applications of the method in computing design floods of small- and medium-size catchment are presented. The results show that, although input requirements for the ITB SUH calculation method are simple and the calculation is easy, the final results agree well with other methods developed previously.
Keywords: mass conserving SUH calculation procedure, ITB SUH calculation method, ITB-1 and ITB-2 SUH, flood hydrograph, hydrology.

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1 Introduction

Flood estimation is one of the most important components of water resources project planning, design and operation. When long flood discharge records (more than 20 years) are available, design floods can be evaluated via a statistical analysis. However, long recorded flood discharge data are seldom availlable to determine design floods of a basin or watershed. This situation is common in many parts of the world, due to lack of gauging stations along rivers and streams. When discharge and rainfall data were not available for planning and designing water management facilities and other hydraulic structures, techniques were developed that allow generation of synthetic unit hydrographs.

The synthetic unit hydrograph method, initially proposed by Sherman in 1922, is still a widely used tool in hydrologic analysis and synthesis, especially for un-ganged watersheds. The term “synthetic” in “synthetic unit hydrograph” denotes the unit hydrograph is derived from watershed characteristics rather than rainfall-runoff data. These methods are popular and play an important role in many water resources design and analyses. These methods are simple, requiring only watershed characteristics, such as catchment area and river length, and serve as useful tools to simulate runoff from un-gagged watersheds.

This paper presents the results of the Capacity Building Research Program, funded by the Institute of Technology Bandung (ITB), Indonesia, 2010. This one-year research project was to develop a new method for calculating synthetic unit hydrographs. This mass conserving SUH calculation procedure, called ITB SUH calculation method, was initially developed by Natakusumah [1] and later implemented by Natakusumah *et al.* [2, 3] for developing ITB-1 and ITB-2 synthetic unit hydrographs.

2 Synthetic unit hydrograph

One of the most popular synthetic unit hydrograph method used is the Soil Conservation Service (SCS) curvilinear unit hydrograph. It is derived from the analysis of large numbers of natural unit hydrographs for catchments of varying size and geographic location. This method is based on the assumption that the same unit hydrograph shape applies to all catchments; only the scale differs.

Following the approach developed by SCS, we derived a unit hydrograph calculation procedure in which the unit hydrograph is dimensionless with axis of $q=Q/Q_p$ and $t=T/T_p$, Q equals the discharge rate at any time T, and Q_p equals the peak discharge at peak time T_p.

To define a complete shape of synthetic unit hydrographs, three characteristics of synthetic unit hydrographs are required. The three characteristics are: 1) basin lag (T_L) and time to peak (T_p), 2) basic shape of synthetic unit hydrograph and 3) adjustable peak discharge (Q_p) per unit rainfall depth.

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2.1 Basin lag and time to peak

The basin lag is an important parameter in computing unit hydrograph, but it is sometimes difficult to estimate its value in real-world situations. Many empirical equations of time lag and its relation to time to peak have been proposed in the literature [5–7]. Our proposed method is flexible in adopting time lag and time to peak formula available in the literature. In this paper, however, we compute the basin lag using a simplified Snyder formula (L_c=1/2 L, n=0.3) as follows:

$$T_L = C_t \; 0.81225 \; L^{0.6} \tag{1}$$

where:

T_L	=	time lag (hours)
C_t	=	Coeff for time calibration (C_t=1 is standard value)
L	=	river length (km)

Furthermore, if T_r is unit rainfall duration, time to peak is given as

$$T_p = t_p + 0.50 \, T_r \tag{2}$$

while time base is defined as

$$T_b = \infty \tag{3.a}$$

But in practice time base is limited to

$$T_b = 10 * T_p \tag{3.b}$$

2.2 Basic shape of synthetic unit hydrograph

Unlike other methods that use specific unit hydrograph shapes, the proposed method is flexible in adopting any basic shape representing unit hydrograph shape (triangular, curvilinear, etc.). Although the proposed method is applicable to any basic shape for synthetic unit hydrographs, in this research, we proposed an adjustable synthetic unit hydrograph shape synthesized by using either a simple single function (ITB-1) or two simple functions (ITB-2) as follows:

a) Single function (ITB-1)

$$q(t) = \exp(2 - t - \tfrac{1}{t})^{\alpha Cp} \qquad (t > 0) \qquad \alpha = 1.500 \tag{4}$$

b) Two functions (ITB-2)

- Rising limb: $q(t) = t^{\alpha} \quad (t > 0) \qquad \alpha = 1.500$ (5.a)

- Recession limb: $q(t) = \exp(1 - t)^{\beta Cp} \quad (t > 1) \quad \beta = 1.000$ (5.b)

where C_t = coefficient for peak discharge calibration (C_p=1.0 is default value). Figure 1 shows the typical shape of ITB-1 and ITB-2 synthetic unit hydrographs generate using equation (4) and (5).

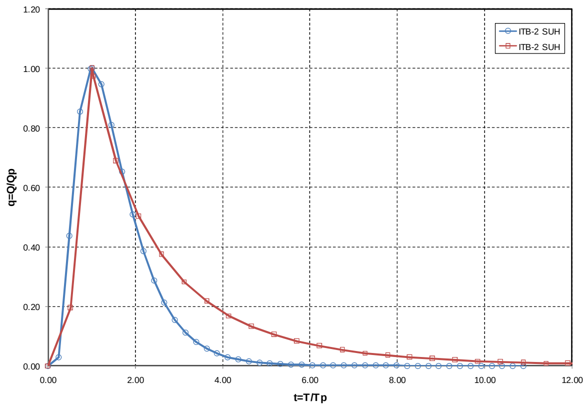


Figure 1: Typical shape of ITB-1 and ITB-2 synthetic unit hydrographs.

2.3 Peak discharge of synthetic unit hydrograph

Peak discharge of the unit hydrograph was derived by following the definition of unit hydrograph and the principle of mass conservation. Figure 2(a) and Figure 2(c) show two typical shapes of unit hydrographs (triangular and curvilinear) of a catchment generated by excess rainfall R (mm). By dividing the abscissa of the unit hydrograph by T_p, and dividing the ordinates and Q_p, we obtain the dimensionless unit hydrograph, shown in Figure 2(b) and Figure 2(d).

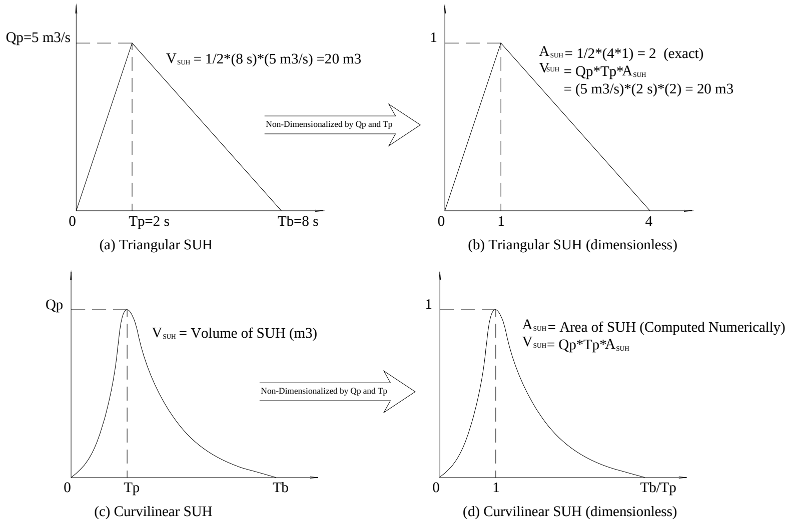


Figure 2: Simple method for calculating volume from unit hydrographs.

By referring to Figure 2, a simple approach for calculating unit hydrograph volume from a dimensionless unit hydrograph is as follows:

$$V_{UH} = Q_p\, T_p\, A_{UH} = Q_p\, T_p\, 3600\, A_{UH} \quad (m^3) \tag{6}$$

where V_{HU} = volume of unit hydrograph (m^3), Q_p = peak of unit hydrograph (m^3/s), A_{UH} = area of unit hydrograph (dimensionless). Please note that A_{UH} can be computed exactly or numerically (e.g. using trapezoidal rule).

The unit hydrograph of a catchment is defined as the direct runoff hydrograph resulting from a unit excess rainfall depth of constant intensity and uniformly distributed over the watershed [4, 5]. Following this definition, the volume of rainfall excess can be computed as

$$V_{RE} = A_{CA}\, R\, 1000 \quad (m^3) \tag{7}$$

where V_{RE} = total volume of unit excess rainfall (m^3), A_{CA} = area of the watershed (km^2), and R= unit excess rainfall depth (mm).

By applying the principle of mass conservation (volume of unit hydrograph = total volume of unit excess rainfall), we obtained

$$Q_p\, T_p\, 3600\, A_{UH} = A_{CA}\, R\, 1000 \tag{8}$$

Therefore the peak discharge can be written as follows:

$$Q_p = \frac{R}{3.6\, T_p} \frac{A_{CA}}{A_{UH}} \quad (m^3/s) \tag{9}$$

in which Q_p = the peak discharge in m^3/s; R= unit excess rainfall depth (mm); A_{CA} = the catchment area (km^2); A_{UH} = the area of unit hydrograph (dimensionless), computed exactly or numerically (e.g. using trapezoidal rule).

2.4 Proposed procedure for developing synthetic unit hydrographs

The proposed procedure used for developing synthetic unit hydrographs is briefly summarized below.

Step-1 : Enter the catchment data such as catchment area (A_{CA}), river length (L) and unit rainfall duration (Tr).

Step-2 : Compute time lag (T_L) using equation (1) or any other time lag formula available. Then compute time to peak (Tp) and time base (Tb) using equations (2) and (3).

Step-3 : Generate ITB-1 and/or ITB-2 dimensionless synthetic unit hydrograph curve using equations (4) and (5), and present them in tabular form.

Step-4 : Compute the area of the dimensionless synthetic unit hydrograph curve generated in step 3 numerically (using the trapezoidal rule).

Step-5 : Compute adjustable peak discharge of the synthetic unit hydrograph Q_p using equation (9).

Step-6 : Generate dimensionalised synthetic unit hydrograph by multiplying the abscissa and ordinate of the dimensionless synthetic unit hydrograph obtained in step 4 by T_p and Q_p respectively.

Step-7 : Compute the total volume of the synthetic unit hydrograph generated in step 6 using the trapezoidal rule. The volume of synthetic unit hydrograph must be equal to 1 mm (unit rainfall excess).

Step-8 : Generate the total hydrograph by performing superposition process of rainfall excess distribution for every unit rainfall duration interval.

Step-9 : Perform final check by computing the total volume of the hydrograph generated in step 8 using the trapezoidal rule. The volume of the hydrograph must be equal to the total volume of rainfall excess.

2.5 Calibration of time to peak and peak discharge values

Suppose, for a particular catchment, the measured unit hydrograph curve is known, and the peak discharge (Q_p) as well as the time to peak (T_p) are easily identifiable. The procedure used for calibrating the computed synthetic unit hydrograph is briefly summarized below.

1) If the time to peak (T_p) of the measured and computed synthetic hydrographs are not similar, the coefficient C_t in equation (1) should be adjusted to bring the times to peak into closer agreement. In general, $C_t < 1.0$ will reduce time to peak, while $C_t > 1.0$ will increase time to peak.

2) If the peak discharges (Q_p) of the measured and computed synthetic hydrographs are not similar, the coefficient C_p in equation (4) and (5) should be adjusted to bring the peak discharges into closer agreement. In general $C_p< 1.0$ will reduce peak discharge, while $C_p> 1.0$ will increase peak discharge.

3 Application

In the following section, two examples application of this new method will be given. The first example demonstrates synthetic unit hydrograph calculations for a small hypothetical basin using a triangular synthetic unit hydrograph. The second example shows the implementation of ITB-1 and ITB-2 synthetic unit hydrographs for calculating flood discharge of Cibatarua river basin, a mid-size basin located in West Java, Indonesia.

3.1 Flood hydrograph of small catchment

The first example application of the ITB method is on a small hypothetical catchment with a catchment area of 1.2 km^2, river length of 1.570 km, and catchment slope of 0001. To show the flexibility of the proposed method, the triangular dimensionless synthetic unit hydrograph shown in Figure 3 was used to generate a flood hydrograph due to excess rainfall of 10 mm, 70mm, and 30 mm (half-hour intervals).

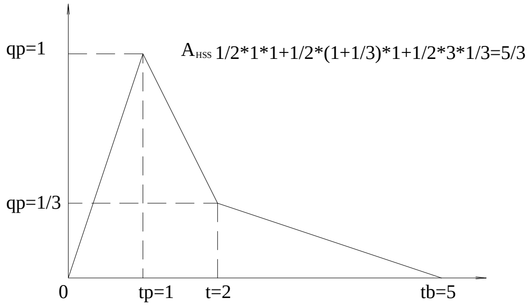


Figure 3: Triangular synthetic unit hydrograph (dimensionless).

Answer

a) Compute time to peak (T_p) and time base (T_b)

- For a small catchment, time concentration is computed using the Kirpirch formula.

$$t_c = 0.01947\ \frac{L^{0.77}}{S^{0.835}} = 0.01947\ \frac{1575^{0.77}}{0.001^{0.835}} = 80.58\text{ min} = 1.34\text{ hour}$$

- Time to peak (T_p) and time base (T_b)

$$Tp = \tfrac{2}{3}\,tc = \tfrac{2}{3}\,1.34 = 0.893\ \text{hour}$$

$$Tb = \tfrac{8}{3}\,tp = \tfrac{8}{3}\,0.893 = 2.382\ \text{hour}$$

b) Compute triangular SUH

1. Compute area of triangular SUH

$$A_{HSS} = A_1 + A_2 + A_3 = (1/2*1*1) + \{1/2*(1+1/3)*1\} + (1/2*3*1/3) = 5/3 \ \leftarrow \text{Exact value}$$

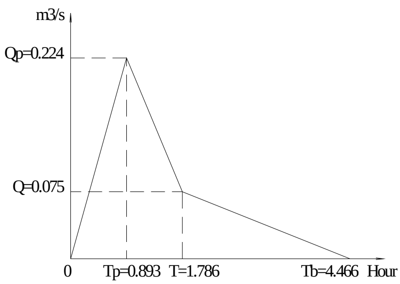
2. Compute peak discharge of SUH

$$Qp = \frac{R}{3.6\,Tp}\frac{A_{CA}}{A_{SUH}} = \frac{1}{3.6(0.893)}\frac{1.2}{1.667} = 0.224\,m^3/s$$

3. Dimensionalised SUH by multiplying the abscissa and ordinate of the dimensionless SUH in Figure 3 by T_p and Q_p, and the result is shown in Figure 4. Ordinates of SUH between 0 and T_p and between T_p and T_b (obtained using linear interpolation) are shown in the table 1.

4. The superposition process of 10 mm, 70 mm, and 30 mm rainfall excess (half-hour intervals), is shown in Table 1, and the final hydrograph result is shown in Figure 5. (Note the ratio of direct run

off (DRO) and rainfall excess (RE) is less than 100% was caused by exclusion of Q_p from superposition process)



T (hour)	Q (m3/s)	Note
0.000	0.000	
0.500	0.126	
0.893	0.225	
1.000	0.203	Tp
1.500	0.123	
1.786	0.075	
2.000	0.069	2*Tp
2.500	0.055	
3.000	0.041	
3.500	0.027	
4.000	0.013	
4.466	0.000	Tb = 5 Tp
4.500	0.000	

Figure 4: Triangular SUH (dimensionalised).

Table 1: Superposition of triangular SUH.

Time (Hour)	Q SUH (m3/s)	SUH Convolution				Volume (m3)
		0.5	1.0	1.5	Total (mm	
		10.0	70.0	30.0	110.0	
0.000	0.000	0.000			0.000	0
0.500	0.125	1.253	0.000		1.253	1,127
1.000	0.202	2.024	8.769	0.000	10.792	10,841
1.500	0.122	1.224	14.167	3.758	19.149	26,948
2.000	0.069	0.687	8.571	6.072	15.330	31,031
2.500	0.055	0.550	4.811	3.673	9.034	21,927
3.000	0.041	0.412	3.849	2.062	6.323	13,821
3.500	0.027	0.275	2.886	1.649	4.811	10,020
4.000	0.014	0.137	1.924	1.237	3.299	7,299
4.500	0.000	0.000	0.962	0.825	1.787	4,577
5.000		0.000	0.000	0.412	0.412	1,979
5.500			0.000	0.000	0.000	371
				Total Volum (m3)		129,570
				C. Area (km2)		1.200
				DRO (mm)		107.98
				DRO/RE (%)		98.16%

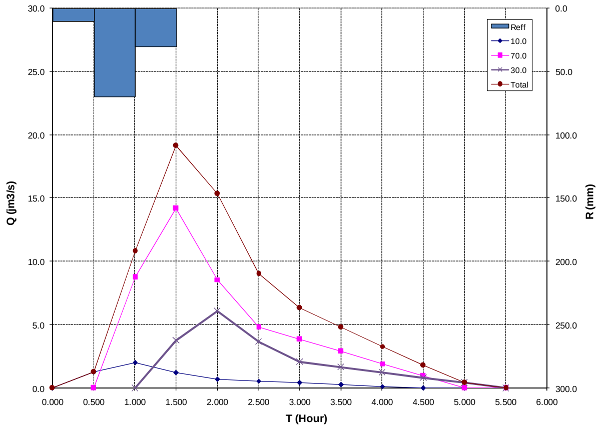


Figure 5: Superposition of triangular SUHs to form a total hydrograph.

3.2 Flood hydrograph of Cibatarua watershed

The second example application of ITB methods is the computation of the flood hydrograph of the Cibatarua river basin. Cibatarua river has catchment area of 56.920 km^2, river length of 12.150 km, and catchment slope of 008. In this example, time lag for ITB-1 SUH was calculated using the Snyder method, while ITB-2 time lag was calculated using the Nakayasu formula. The calculation procedures for generating ITB-1 and ITB-2 SUH are shown in Table 3 and Table 4.

Furthermore, the incremental rainfall excess shown in Table 2 used to generate the total hydrographs, using the superposition process shown in Table 5 and Table 6. The resulting total hydrographs were compared with the results other methods shown in Figure 6. This figure shows that the results of HSS ITB-1 are close to those of the Snyder-Alexeyev and HEC-HMS results, while the ITB HSS-2 (with $\alpha = 1.50$ and non-default $\beta = 0.72$) are close to the Nakayasu results ($\alpha = 3.00$ for Nakayasu).

Table 2: Rainfall excess distribution.

Time (Hr)	RE (mm)
1.000	55.400
2.000	16.100
3.000	11.700
4.000	9.200
5.000	7.200
6.000	5.700

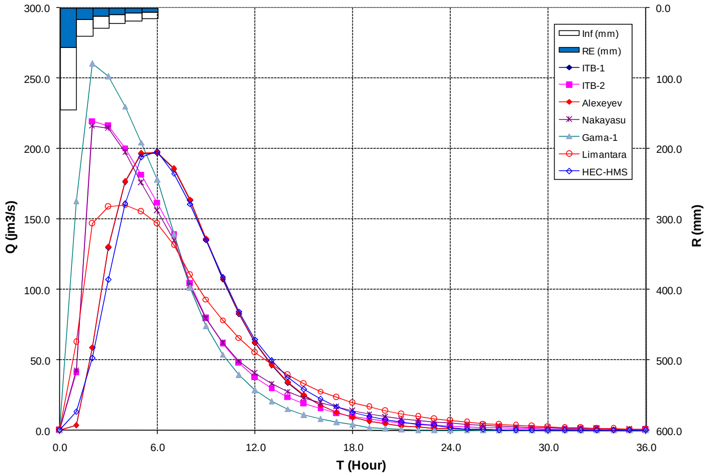


Figure 6: Comparison results of ITB HSS-and HSS ITB-2 with the results of Snyder-Alexeyev, Nakayasu, Limantara, GAMA-1, and HEC-HMS.

Table 3: ITB-1 SUH calculation for Cibatarua Basin (time lag Snyder).

I. Characteristic of Watershed and Rainfall Excess

1. River Name	=	Cibatarua	
2. Cathment Area (A)	=	56.92	Km^2
3. River Lenght (L)	=	12.15	Km
4. Unit Rainfall Excess (R)	=	1.00	mm
5. Unit Rainfall Duration (Tr)	=	1.00	Hour

II. Computation of Time Peak (Tp) and Time Base (Tb)

1. Time Coefficient (C_t)	=	1.00	
2. Time Lag --> Snyder		2	
LC = 0.5*L	=	6.075	km
TL = $Ct(LxLC)^n$	=	3.634	Hour
Te = tp/5.5	=	0.661	Hour
TP = TL+0.25(Tr-Te) → Te > Tr TP = TL+0.50Tr → Te < Tr		4.134	Hour
3. Time to Peak			
Tp =	=	4.134	Hour
4. Time Base			
T_B/T_P	=	10	(Ratio T_B/T_P)
T_B	=	41.34	Hour

III. Peak Discharge (QP)

1. Peak Coefficient (C_p)	=	1.000	
2. Alpha	=	1.500	
3. Area of SUH (Sum Col-4 Part IV)	=	1.613	
4. Qp = 1/(3.6Tp)*(A_{DAS}/A_{HSS})	=	2.370	m3/s
5. Rainfall Volume (=R*A_{DAS}*100(	=	56,920	m3
6. Volume of SUH (V_{SUH})	=	56,920	m3
7. Rainfall Depth	=	1.000	mm

IV. Computation of ITB-1 SUH :

T	SUH (dimensionless)			SUH (dimensionalised)	
(hour)	t=T/Tp	q=Q/Qp	A	Q(m3/s)	V(m3)
(1)	(2)	(3)	(4)	(5)	(6)
0.00	0.00000	0.00000	0.00000	0.00000	0.0000
1.00	0.24187	0.02831	0.00342	0.06711	120.7954
2.00	0.48374	0.43760	0.05635	1.03725	1987.8489
3.00	0.72561	0.85587	0.15643	2.02866	5518.6460
4.00	0.96748	0.99836	0.22424	2.36641	7911.1317
4.13	1.00000	1.00000	0.03249	2.37029	1146.1919
5.00	1.20936	0.94709	0.20382	2.24488	7190.5209
6.00	1.45123	0.81022	0.21252	1.92046	7497.6064
7.00	1.69310	0.65338	0.17700	1.54870	6244.4931
8.00	1.93497	0.50780	0.14043	1.20364	4954.2235
9.00	2.17684	0.38507	0.10798	0.91273	3809.4690
10.00	2.41871	0.28701	0.08128	0.68030	2867.4530
11.00	2.66058	0.21126	0.06026	0.50075	2125.8966
12.00	2.90245	0.15405	0.04418	0.36514	1558.6070
13.00	3.14432	0.11152	0.03212	0.26434	1133.0651
14.00	3.38620	0.08028	0.02320	0.19028	818.3158
15.00	3.62807	0.05752	0.01667	0.13635	587.9357
16.00	3.86994	0.04107	0.01192	0.09734	420.6509
17.00	4.11181	0.02923	0.00850	0.06929	299.9368
18.00	4.35368	0.02075	0.00604	0.04919	213.2601
19.00	4.59555	0.01470	0.00429	0.03485	151.2732
20.00	4.83742	0.01040	0.00304	0.02464	107.0893
21.00	5.07929	0.00734	0.00215	0.01740	75.6814
22.00	5.32116	0.00518	0.00151	0.01227	53.4067
23.00	5.56303	0.00365	0.00107	0.00864	37.6401
24.00	5.80491	0.00257	0.00075	0.00608	26.4988
25.00	6.04678	0.00180	0.00053	0.00427	18.6371
26.00	6.28865	0.00127	0.00037	0.00300	13.0967
27.00	6.53052	0.00089	0.00026	0.00211	9.1963
28.00	6.77239	0.00062	0.00018	0.00148	6.4531
29.00	7.01426	0.00044	0.00013	0.00104	4.5255
30.00	7.25613	0.00031	0.00009	0.00073	3.1720
31.00	7.49800	0.00021	0.00006	0.00051	2.2222
32.00	7.73987	0.00015	0.00004	0.00036	1.5561
33.00	7.98175	0.00011	0.00003	0.00025	1.0892
34.00	8.22362	0.00007	0.00002	0.00017	0.7621
35.00	8.46549	0.00005	0.00002	0.00012	0.5331
36.00	8.70736	0.00004	0.00001	0.00009	0.3728
37.00	8.94923	0.00003	0.00001	0.00006	0.2606
38.00	9.19110	0.00002	0.00001	0.00004	0.1821
39.00	9.43297	0.00001	0.00000	0.00003	0.1273
40.00	9.67484	0.00001	0.00000	0.00002	0.0889
41.00	9.91671	0.00001	0.00000	0.00001	0.0621
42.00	10.15859	0.00000	0.00000	0.00000	0.0255
43.00	10.40046	0.00000	0.00000	0.00000	0.0000
44.00	10.64233	0.00000	0.00000	0.00000	0.0000
45.00	10.88420	0.00000	0.00000	0.00000	0.0000
		Area SUH	1.6134085	Vol (m3)	56920.000
				DRO (mm)	1.000

Remarks

Col-1	: Given Time Interval (Hour) → $T_i = T_{i-1} + Tr$
Col-2	: Dimensionless Time t=T/Tp → Kolom-1 /Tp
Col-3	: Dimensionless Ordinate q=Q/Qp from ITB-1 Equation Curve
Col-4	: Area of SUH → $A_i = ½ \times (t_i - t_{i-1}) \times (q_i + q_{i-1})$ (dimensionless)
	: Sum of Column-4 = A_{SUH} (Important for Computing Qp)
Col-5	: Dimensionalised Qi → $Q_i = q_i \times Qp$ (Kolom 3 x Qp)
Col-6	: Area of SUH (m3) → $A_i = ½ \times 3600 \times (T_i - T_{i-1}) \times (Q_i + Q_{i-1})$
	: Sum of Column-6 (V_{SUH}) if divided by A_{CA} shoild be = 1

Table 4: ITB-2 SUH calculation for Cibatarua Basin (time lag Nakayasu).

I. Characteristic of Watershed and Rainfall Excess

1. River Name	=	Cibatarua	
2. Cathment Area (A)	=	56.92	Km^2
3. River Lenght (L)	=	12.15	Km
4. Unit Rainfall Excess (R)	=	1.00	mm
5. Unit Rainfall Duration (Tr)	=	1.00	Jam

II. Computation of Time Peak (Tp) and Time Base (Tb)

1. Time Coefficient (C_t)		=	1.00	
2. Time Lag --> Nakayasu			1	
TL = $Ct*0.21*L^{0.7}$ = Ct*(0.527 + 0.058*L)	< 15 km ≥ 15 km		1.206	Jam
TP = 1.6 TL		=	1.930	Jam
3. Time to Peak				
Tp =		=	1.930	Jam
4. Time Base				
T_B/T_P		=	20	(Ratio T_B/T_P)
T_B		=	38.60	Jam

III. Peak Discharge (QP)

1. Peak Coefficient (C_p)	=	1.000	
2. Alpha	=	2.500	
3. Betha	=	0.720	
4. Area of SUH (Sum Col-4 Part IV)	=	2.127	
5. Qp = 1/(3.6Tp)*(A_{DAS}/A_{HSS})	=	3.851	m3/s
6. Rainfall Volume (=R*ADAS*10(	=	56,920	m3
7. Volume of SUH (VSUH)		56,920	m3
8. Rainfall Depth	=	1.000	mm

IV. Computation of ITB-2 SUH :

T	SUH (dimensionless)			SUH (dimensionalised)	
(Hour)	t=T/Tp	q=Q/Qp	A	Q(m3/s)	V(m3)
(1)	(2)	(3)	(4)	(5)	(6)
0.00	0.00000	0.00000	0.00000	0.00000	0.0000
1.00	0.51815	0.19326	0.05007	0.74431	1339.7578
1.93	1.00000	1.00000	0.28749	3.85133	7692.5589
2.00	1.03630	0.97433	0.03584	3.75245	958.9665
3.00	1.55446	0.68809	0.43069	2.65004	11524.4951
4.00	2.07261	0.50156	0.30821	1.93169	8247.1234
5.00	2.59076	0.37360	0.22673	1.43885	6066.9674
6.00	3.10891	0.28281	0.17006	1.08921	4550.4997
7.00	3.62707	0.21684	0.12945	0.83512	3463.7900
8.00	4.14522	0.16800	0.09970	0.64703	2667.8759
9.00	4.66337	0.13132	0.07755	0.50574	2074.9949
10.00	5.18152	0.10342	0.06081	0.39830	1627.2813
11.00	5.69967	0.08199	0.04804	0.31577	1285.3325
12.00	6.21783	0.06538	0.03818	0.25180	1021.6342
13.00	6.73598	0.05241	0.03052	0.20185	816.5789
14.00	7.25413	0.04221	0.02451	0.16257	655.9566
15.00	7.77228	0.03414	0.01978	0.13150	529.3221
16.00	8.29043	0.02773	0.01603	0.10678	428.9030
17.00	8.80859	0.02260	0.01304	0.08703	348.8544
18.00	9.32674	0.01848	0.01064	0.07116	284.7394
19.00	9.84489	0.01516	0.00871	0.05837	233.1623
20.00	10.36304	0.01247	0.00716	0.04802	191.5045
21.00	10.88120	0.01028	0.00589	0.03961	157.7335
22.00	11.39935	0.00851	0.00487	0.03276	130.2616
23.00	11.91750	0.00705	0.00403	0.02716	107.8422
24.00	12.43565	0.00586	0.00334	0.02256	89.4909
25.00	12.95380	0.00488	0.00278	0.01879	74.4273
26.00	13.47196	0.00407	0.00232	0.01567	62.0294
27.00	13.99011	0.00340	0.00194	0.01310	51.8000
28.00	14.50826	0.00285	0.00162	0.01097	43.3398
29.00	15.02641	0.00239	0.00136	0.00921	36.3272
30.00	15.54457	0.00201	0.00114	0.00774	30.5019
31.00	16.06272	0.00169	0.00096	0.00651	25.6532
32.00	16.58087	0.00143	0.00081	0.00549	21.6095
33.00	17.09902	0.00120	0.00068	0.00464	18.2309
34.00	17.61717	0.00102	0.00058	0.00392	15.4030
35.00	18.13533	0.00086	0.00049	0.00332	13.0321
36.00	18.65348	0.00073	0.00041	0.00281	11.0411
37.00	19.17163	0.00062	0.00035	0.00239	9.3664
38.00	19.68978	0.00053	0.00030	0.00203	7.9558
39.00	20.20793	0.00000	0.00014	0.00000	3.6553
40.00	20.72609	0.00000	0.00000	0.00000	0.0000
41.00	21.24424	0.00000	0.00000	0.00000	0.0000
42.00	21.76239	0.00000	0.00000	0.00000	0.0000
43.00	22.28054	0.00000	0.00000	0.00000	0.0000
44.00	22.79870	0.00000	0.00000	0.00000	0.0000
45.00	23.31685	0.00000	0.00000	0.00000	0.0000
		Area SUH	2.1272046	Vol (m3)	56920.000
				DRO (mm)	1.000

Remarks

Col-1	: Given Time Interval (Hour) → $T_i = T_{i-1} + Tr$
Col-2	: Dimensionless Time t=T/Tp → Kolom-1 /Tp
Col-3	: Dimensionless Ordinate q=Q/Qp from ITB-2 Equation Curve
Col-4	: Area of SUH → $A_i = ½ \times (t_i - t_{i-1}) \times (q_i + q_{i-1})$ (dimensionless)
	: Sum of Column-4 = A_{SUH} (Important for Computing Qp)
Col-5	: Dimensionalised Qi → $Q_i = q_i \times Qp$ (Kolom 3 x Qp)
Col-6	: Area of SUH (m3) → $A_i = ½ \times 3600 \times (T_i - T_{i-1}) \times (Q_i + Q_{i-1})$
	: Sum of Column-6 (V_{SUH}) if divided by A_{CA} shoild be = 1

Table 5: Superposition of ITB-1 UH.

Time (hour)	ITB-1 SUH	Hydrograph Convolution						Total	Vol Hyd (m3)
		1	2	3	4	5	6		
		55.40	16.10	11.70	9.20	7.20	5.70	105.300	
0.0	0.00	0.00						0.00	0
1.00	0.07	3.72	0.00					3.72	6692
2.00	1.04	57.46	1.08	0.00				58.54	112072
3.00	2.03	112.39	16.70	0.79	0.00			129.87	339151
4.00	2.37	131.10	32.66	12.14	0.62	0.00		176.51	551496
5.00	2.24	124.37	38.10	23.74	9.54	0.48	0.00	196.23	670933
6.00	1.92	106.39	36.14	27.69	18.66	7.47	0.38	196.74	707335
7.00	1.55	85.80	30.92	26.27	21.77	14.61	5.91	185.27	687617
8.00	1.20	66.68	24.93	22.47	20.65	17.04	11.56	163.34	627502
9.00	0.91	50.57	19.38	18.12	17.67	16.16	13.49	135.38	537702
10.00	0.68	37.69	14.69	14.08	14.25	13.83	12.80	107.34	436898
11.00	0.50	27.74	10.95	10.68	11.07	11.15	10.95	82.54	341787
12.00	0.37	20.23	8.06	7.96	8.40	8.67	8.83	62.14	260434
13.00	0.26	14.64	5.88	5.86	6.26	6.57	6.86	46.07	194786
14.00	0.19	10.54	4.26	4.27	4.61	4.90	5.20	33.78	143731
15.00	0.14	7.55	3.06	3.09	3.36	3.61	3.88	24.55	104994
16.00	0.10	5.39	2.20	2.23	2.43	2.63	2.85	17.73	76108
17.00	0.07	3.84	1.57	1.60	1.75	1.90	2.08	12.74	54838
18.00	0.05	2.73	1.12	1.14	1.25	1.37	1.51	9.11	39325
19.00	0.03	1.93	0.79	0.81	0.90	0.98	1.08	6.50	28091
20.00	0.02	1.37	0.56	0.58	0.64	0.70	0.78	4.62	20003
21.00	0.02	0.96	0.40	0.41	0.45	0.50	0.55	3.27	14206
22.00	0.01	0.68	0.28	0.29	0.32	0.35	0.39	2.32	10067
23.00	0.01	0.48	0.20	0.20	0.23	0.25	0.28	1.64	7121
24.00	0.01	0.34	0.14	0.14	0.16	0.18	0.20	1.16	5028
25.00	0.00	0.24	0.10	0.10	0.11	0.13	0.14	0.81	3546
26.00	0.00	0.17	0.07	0.07	0.08	0.09	0.10	0.57	2498
27.00	0.00	0.12	0.05	0.05	0.06	0.06	0.07	0.40	1758
28.00	0.00	0.08	0.03	0.04	0.04	0.04	0.05	0.28	1236
29.00	0.00	0.06	0.02	0.02	0.03	0.03	0.03	0.20	868
30.00	0.00	0.04	0.02	0.02	0.02	0.02	0.02	0.14	609
31.00	0.00	0.03	0.01	0.01	0.01	0.02	0.02	0.10	427
32.00	0.00	0.02	0.01	0.01	0.01	0.01	0.01	0.07	300
33.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.05	210
34.00	0.00	0.01	0.00	0.00	0.00	0.01	0.01	0.03	147
35.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.02	103
36.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	72
37.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	50
38.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	35
39.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	25
40.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	17
41.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	12
42.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	7
43.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4
44.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2
45.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1
46.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1
47.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
48.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
49.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
50.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
						Vol Hydrograf		m3	6E+06
						Cathment Area		km2	56.92
						Direct Run Off		mm	105.23
						Rasio DRO/RE		%	99.9%

Table 6: Superposition of ITB-2 UH.

Time (hour)	ITB-2 SUH	Hydrograph Convolution						Total	Vol Hyd (m3)
		1	2	3	4	5	6		
		55.40	16.10	11.70	9.20	7.20	5.70	105.300	
0.0	0.00	0.00						0.00	0
1.00	0.74	41.23	0.00					41.23	74223
2.00	3.75	207.9	11.98	0.00				219.87	469987
3.00	2.65	146.81	60.41	8.71	0.00			215.94	784448
4.00	1.93	107.02	42.67	43.90	6.85	0.00		200.4	749463
5.00	1.44	79.71	31.10	31.01	34.52	5.36	0.00	181.70	687838
6.00	1.09	60.34	23.17	22.60	24.38	27.02	4.24	161.75	618207
7.00	0.84	46.27	17.54	16.83	17.77	19.08	21.39	138.88	541127
8.00	0.65	35.85	13.45	12.74	13.24	13.91	15.11	104.29	437693
9.00	0.51	28.02	10.42	9.77	10.02	10.36	11.01	79.60	330989
10.00	0.40	22.07	8.14	7.57	7.68	7.84	8.20	61.51	253985
11.00	0.32	17.49	6.41	5.92	5.95	6.01	6.21	48.00	197106
12.00	0.25	13.95	5.08	4.66	4.65	4.66	4.76	37.77	154374
13.00	0.20	11.18	4.05	3.69	3.66	3.64	3.69	29.92	121843
14.00	0.16	9.01	3.25	2.95	2.91	2.87	2.88	23.86	96809
15.00	0.13	7.28	2.62	2.36	2.32	2.27	2.27	19.12	77368
16.00	0.11	5.92	2.12	1.90	1.86	1.81	1.80	15.40	62153
17.00	0.09	4.82	1.72	1.54	1.50	1.45	1.44	12.46	50162
18.00	0.07	3.94	1.40	1.25	1.21	1.17	1.15	10.12	40656
19.00	0.06	3.23	1.15	1.02	0.98	0.95	0.93	8.25	33079
20.00	0.05	2.66	0.94	0.83	0.80	0.77	0.75	6.75	27009
21.00	0.04	2.19	0.77	0.68	0.65	0.63	0.61	5.54	22126
22.00	0.03	1.81	0.64	0.56	0.54	0.51	0.50	4.56	18180
23.00	0.03	1.50	0.53	0.46	0.44	0.42	0.41	3.76	14981
24.00	0.02	1.25	0.44	0.38	0.36	0.35	0.33	3.11	12377
25.00	0.02	1.04	0.36	0.32	0.30	0.29	0.27	2.58	10251
26.00	0.02	0.87	0.30	0.26	0.25	0.24	0.23	2.15	8511
27.00	0.01	0.73	0.25	0.22	0.21	0.20	0.19	1.79	7081
28.00	0.01	0.61	0.21	0.18	0.17	0.16	0.15	1.49	5905
29.00	0.01	0.51	0.18	0.15	0.14	0.14	0.13	1.25	4933
30.00	0.01	0.43	0.15	0.13	0.12	0.11	0.11	1.05	4129
31.00	0.01	0.36	0.12	0.11	0.10	0.09	0.09	0.88	3463
32.00	0.01	0.30	0.10	0.09	0.08	0.08	0.07	0.74	2909
33.00	0.00	0.26	0.09	0.08	0.07	0.07	0.06	0.62	2447
34.00	0.00	0.22	0.07	0.06	0.06	0.06	0.05	0.52	2062
35.00	0.00	0.18	0.06	0.05	0.05	0.05	0.04	0.44	1741
36.00	0.00	0.16	0.05	0.05	0.04	0.04	0.04	0.37	1471
37.00	0.00	0.13	0.05	0.04	0.04	0.03	0.03	0.32	1245
38.00	0.00	0.11	0.04	0.03	0.03	0.03	0.03	0.27	1055
39.00	0.00	0.00	0.03	0.03	0.03	0.02	0.02	0.13	723
40.00	0.00	0.00	0.00	0.02	0.02	0.02	0.02	0.08	392
41.00	0.00	0.00	0.00	0.00	0.02	0.02	0.02	0.05	246
42.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.03	144
43.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	72
44.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	21
45.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
46.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
47.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
48.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
49.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
50.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
						Vol Hydrograf		m3	6E+06
						Cathment Area		km2	56.92
						Direct Run Off		mm	104.27
						Rasio DRO/RE		%	99.0%

4 Conclusions

The unit hydrograph methods are still widely used tool in hydrologic analysis. These methods are simple, requiring only an easy determination of watershed characteristics, such as catchment area and river length. This paper, presents a new synthetic unit hydrograph computation method based on mass conservation principle. This mass conserving SUH calculation procedure, called ITB ITB SUH calculation method, has been implemented to develop ITB-1 and ITB-2 SUH. Our proposed method is flexible in adopting time lag and time to peak formula available in the literature. The method is applicable to any basic shape for synthetic unit hydrographs.

We derive a unit hydrograph calculation procedure in which the dimensionless synthetic unit hydrograph basic shape synthesized by using either a simple single function (ITB-1) or two simple functions (ITB-2). The peak discharge is then computed using terms involving time to peak and the ratio between catchment area and the area of unit hydrograph computed using trapezoidal rule. The computed time to peak and peak discharge value are then used to change the dimensionless unit hydrograph into dimensionalised unit hydrograph.

The derivation of peak discharge using our method is simple and easy to understand. Using such derivations, it is easy to teach students how to develop a synthetic unit hydrograph and corresponding peak discharge using different types of basic shapes suitable for unit hydrograph development. Unlike the peak discharge formula of other methods, which applies only to certain basic hydrograph shape (e.g. the Nakayasu peak discharge formula applies only to curves according Nakayasu etc), the proposed peak discharge formula applies for any basic hydrograph shape.

Finally some applications of the ITB SUH calculation method in computing design flood of small and medium size catchment are also presented. The results show that, although input data required by ITB-1 and ITB-2 synthetic unit hydrograph are simple and the calculation is easy, but the final results agree well with other methods developed earlier.

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