Determination of Rainfall-Runoff Characteristics in An Urban Area: Sungai Kerayong Catchment, Kuala Lumpur

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ABSTRACT

Rainfall-runoff characteristics of Sungai Kerayong catchment will be discussed in this article. The catchment represents an urban catchment with rapid growth rate due to urbanization process. A total of 90 independent storm events which were selected randomly for 5 years period were analyzed to determine the rainfall-runoff relationship. The catchment which has the area of 48.3km^2 was divided into three sub catchments and the landuse map of the area was created using digital topographic maps and satellite images. The amount of runoff generated was estimated and the analysis was carried out by selecting storm events randomly. Finally, a linear regression between rainfall depth and amount of runoff generated indicates 77 % of impervious area in the catchment with estimated depression storage of 1.4mm. Further, the estimation of time of concentration (t_c) will be discussed. The estimation of t_c will be based by assessment on a total of 20 direct runoff hydrographs from the catchment. The t_c is defined as the time between the center of mass rainfall excess and the inflection point on the recession of the direct runoff hydrograph. The average value of t_c obtained from the analyzed hydrographs is 139 minutes and will be compared with four empirical time of concentration equations. The results indicated that the Yen and Chow's Simplified Formula give the best estimation of t_c compared to the Bransby-Williams, National Association of Australian State Road Authorities (NAASRA) and Kerby's Formula.

KEYWORDS
Urban catchment, hydrological response, rainfall-runoff relationships, time of concentration.

INTRODUCTION
Hydrological studies have been increasingly important in urban areas. Most of the drainage system concepts and designs need to be addressed properly in order to maintain their efficiency. The hydrological processes in urban areas similar to those in rural areas but they occur at smaller temporal and spatial scales in urban areas than in rural regions (Delleur, 2003). This brings fundamental differences with respect to theory, data collections and calculation methods. It is important to note that even though there is lots of information regarding runoff generation, the number of investigations in the context of tropical climate is scarce.

One of the other significant parameter required is the time of concentration (t_c) of a catchment area. By definition, it has two general descriptions. The time of concentration is defined as the flow travel time from the most hydraulically remote point in the contributing catchment area to the point under study (MSMA, 2000). The second definition is the t_c is based on a rainfall hyetograph and the resulting runoff hydrograph. It is the time between the center of mass rainfall excess and the inflection point on the recession of the direct runoff hydrograph (McCuen, 1989). Meanwhile, Wong (2005) has demonstrated nine time of concentration formulas published between 1946-1993 and found out that formulas that do not account for the rainfall intensity are only valid for a limited range of intensities. Time of concentration can be a valuable input in formulating new methods in hydrological studies. It can be considered as a system memory in expanding the rational method into the rational hydrograph methods (Guo, 2001). Large errors can always be expected in estimating time of concentration from commonly used equations and lead to significant errors in design discharge (Chin, 2000).

It is hope that this study will provide basic idea of urban runoff generation in relation to tropical climate rainfall conditions. Therefore, the main objectives of this study are to create landuse map to evaluate the impervious and pervious area of the catchment and to develop a reliable rainfall-runoff relationship which represents urban area. Further this article will add information in estimating time of concentration in urban catchment. The pattern of time of concentration obtained from direct runoff hydrographs and make comparison by using existing time of concentration equations.

STUDY SITE AND METHODOLOGY

Sungai Kerayong catchment area is located in Wilayah Persekutuan Kuala Lumpur and has been one of the major tributaries of Klang River. The total area of the catchment is estimated at 48.3km^2 and for this particular research; it has been divided into three sub catchments namely Kg. Cheras Baru , Taman Miharja and Taman Desa (downstream). In order to establish the relationship between rainfall and runoff, the acquisition of significant data is imminent. The main data type to be analyzed in this study is the rainfall and the water level data. The data was obtained from Humid Tropics Centre, Kuala Lumpur (HTCKL) and Malaysian Department of Irrigation and Drainage (DID).

The water level data is used for calculation of runoff generated in the area and the rainfall data then will be used to analyze the correlation of both properties. The data analyzed were from year 1998 to 2003 with 15 minutes intervals. The summary of hydrological stations available in Sungai Kerayong catchment is presented in Table 1. The rainfall stations are indicated by the initial 'R' and then followed by their particular serial numbers whereas the water level stations are indicated by the initial letter 'W'.

A survey was carried out to determine the cross sections of the channels for each sub catchments (Liew, 2004). The Manning Equation is used to establish the discharge curves of the stream flow. A total of 90 storm events were analyzed and 20 direct runoff hydrographs were selected and matched with corresponding rainfall hyetographs to determine the time of concentration. The summary of this study can be concluded in a flow chart as shown in Figure 1.

Further, four equations are selected to compare with the manual findings using the direct runoff hydrographs method. The equations are the Bransby-Williams (Eq.1), Yen and Chow's Simplified Formula (Eq.2), National Association of Australian State Road Authorities (NAASRA) (Eq.3) and Kerby's Formula (Eq.4). The equations are shown as follow.

Table 1: Sungai Kerayong Hydrological Stations

Station Name	Station No.	Latitude	Longitude	Type of Instrument
Kg. Cheras Baru	R3117101 W0000001	03° 06.477' 03° 06.603'	101° 44.657' 101° 44.745'	RF 14 Data Logger WL 14 Data Logger
Pandan Indah	- W0000002	- 03° 07.603'	- 101° 45.044'	- WL 14 Data Logger
Taman Miharja	R3117102 W0000003	03° 07.312' 03° 07.438'	101° 43.685' 101° 43.690'	RF 14 Data Logger WL 14 Data Logger
Taman Sg. Besi	R3016102 W0000004	03° 05.808' 03° 05.508'	101° 41.832' 101° 41.832'	RF 14 Data Logger SEBA WL Recorder
Taman Desa	R3016103 W0000005	03° 05.743' 03° 05.738'	101° 40.676' 101° 40.674'	RF 14 Data Logger WL 14 Data Logger

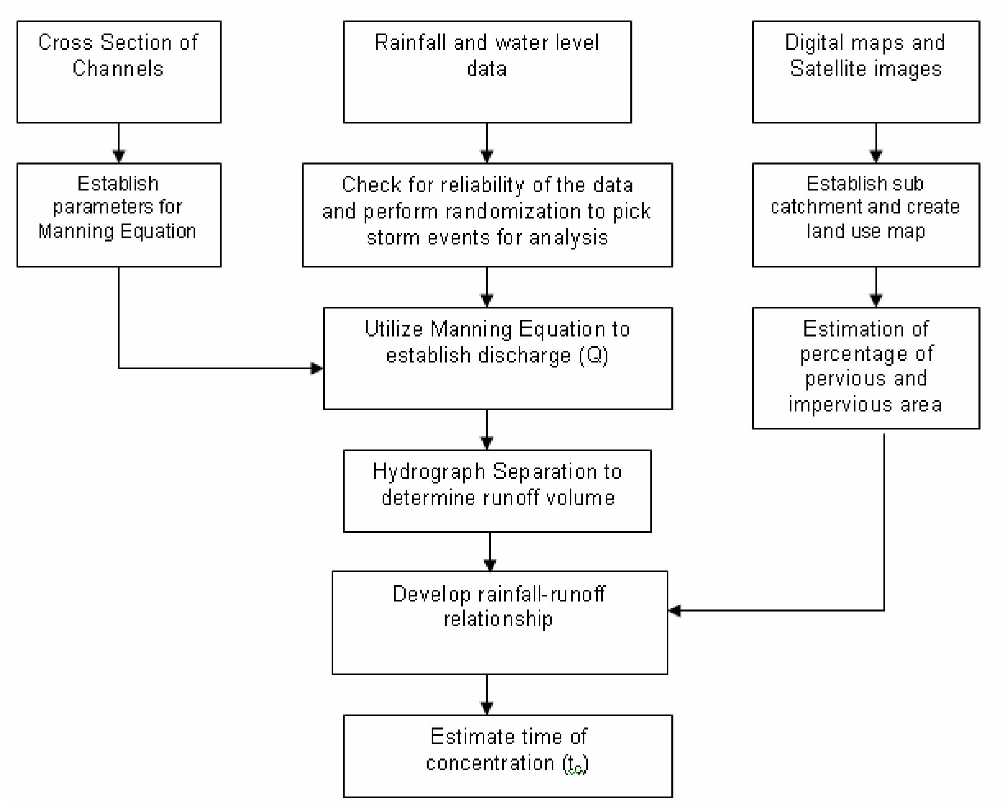

Figure 1: Flow chart of research activities

Bransby-Williams (1977) Formula

$$t_c = \frac{58L}{A^{0.1}S^{0.2}} \tag{1}$$

where t_c = Time of concentration (min)
L = Mainstream length (km)
A = Catchment area (km^2)
S = Equal Area Slope (m/km)

Yen and Chow's (1983) Simplified Formula

$$t_o = 1.2\left(\frac{nL_o}{S_o^{0.5}}\right)^{0.6} \tag{2}$$

where t_o = Time of overland flow (min)
n = Manning's resistance coefficient for overland surface.
L_o = Length of overland plane (m)
S_o = Overland slope (m/m)

National Association of Australian State Road Authorities (1986) Formula

$$t_o = \frac{42.6\, N\, L^{0.333}}{S_o^{\ 0.2}} \tag{3}$$

where t_o = Time of overland flow (min)
N = Retardance coefficient
L = Length of overland plane (m)
S_o = Overland slope (m/m)

Kerby's Formula

$$t_c = 1.45\left(\frac{N_k L_o}{S_o^{\ 0.5}}\right)^{0.467} \tag{4}$$

where t_o = Time of overland flow (min)
N_k= Kerby's resistance coefficient.
L_o = Length of overland plane(m)
S_o = Overland slope (m/m)

Finally, the goodness of fit between the estimated and the observed times of concentration is measured by an objective function (Wong, 2005; Nash and Sutcliffe, 1970), defined as:

$$N.S = 1 - \frac{\sum \left(t_{oo} - t_{oe}\right)^2}{\sum \left(t_{oo} - t_{om}\right)^2} \tag{5}$$

where t_{oo} = observed overland time of concentration
t_{oe} = estimated overland time of concentration
t_{om}= mean of all the observed times of concentration.

A perfect agreement between the estimated and the observed gives a value of unity for N.S function while negative value indicates a poor agreement. Even if the value is negative, it is still considered as relevant as the negative sign just signifies the variance between the observed and the estimated is even greater than the variance among the observed values. The negative value may occur due to the increasing error and can be theoretically being N.S equals to negative infinity.

RESULTS AND DISCUSSION

As stated before, a land use map was created by using satellite images and digital topographic maps. From the created map, the percentage of impervious surface was estimated using AutoCAD and further, the land use characteristics was classified into eight major categories. The created land use map is shown in Figure 2 and the summary of the estimations result is presented in Table 2.

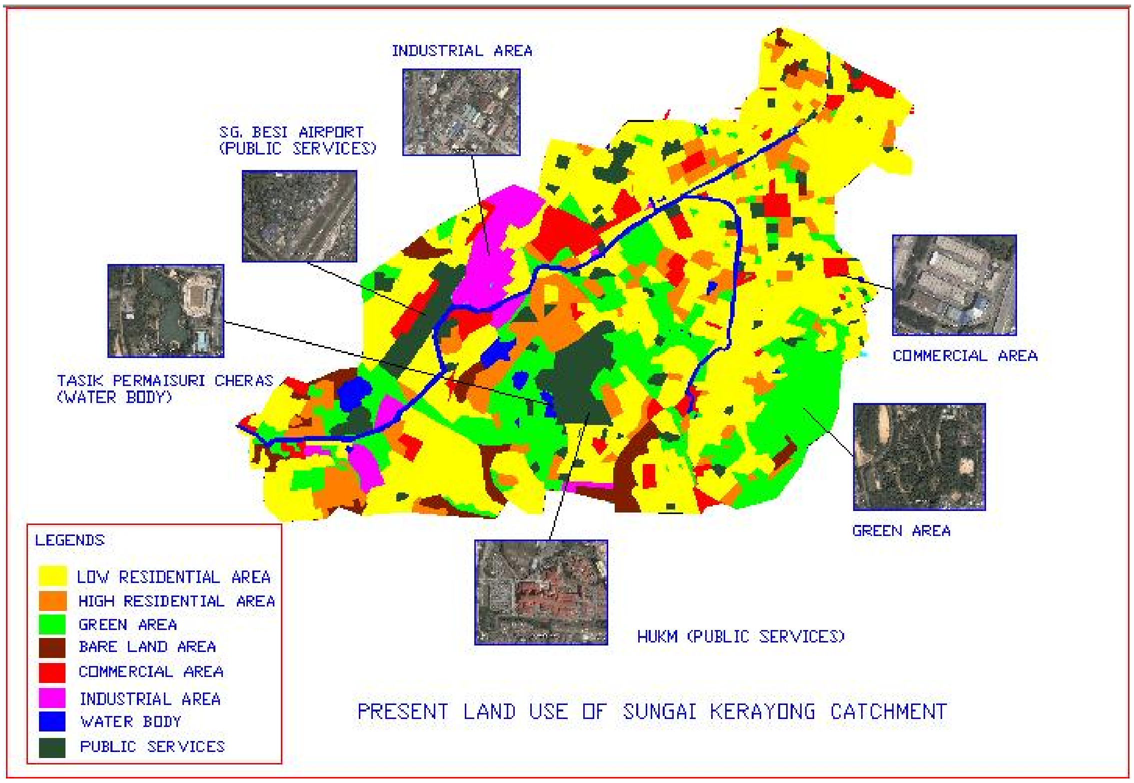

Figure 2: Land use map of Sungai Kerayong catchment

Table 2: Land use compositions in Sungai Kerayong catchment

Categories	**Area (km^2)**
Pervious Area and Water Bodies	
Green Area	8.47
Bare Land Area	1.83
Water Bodies	0.55
Total	10.85
Percentage	**22.5%**
Impervious Area	
Industrial Area	1.86
Commercial Area	2.66
Public Services Area	3.47
High Residential Area	5.44
Low Residential Area	24.04
Total Impervious Area	37.46
Percentage	**77.5%**

The study area is highly urbanized with 77.5% of imperviousness. Low residential area formed the largest fraction of the impervious surfaces covering 24.0% of the catchment. While the definition of urban catchment remains to be argued, the level of imperviousness is strongly regarded as an important factor and widely accepted by hydrologists. The percentage of impervious area will be compared with the value obtained from the linear regression of rainfall and runoff events in the catchment.

Rainfall and Runoff Analysis

In general, the event basis analysis comprises of the rainfall events separation, identification of typical events of different magnitudes, the derivation of characteristics parameters and statistical interpretation (Merz et al., 2006). However, for this particular study, the emphasis is more to determine the amount of runoff generated by different storm events. A total of 90 storm events for a period of 5 years (1998-2003) were selected randomly throughout the catchment. The event analysis involved constructing the hydrographs and hyetographs to find the correlation of the amount of rainfall and volume of runoff generated during the storm. In this study, the method used for the baseflow separation is the constant-discharge technique. McCuen (2005) defines the technique as the line which separates the baseflow and the direct runoff begins at the point of the lowest discharge rate at the start of flood runoff and extends at a constant rate until it intersects the recession limb of the hydrograph.

The rainfall-runoff relationship for Sungai Kerayong indicates a good correlation between both properties with R^2 of 0.94 ($p<0.05$). The estimated impervious surface was 76.2% and the depression storage was 1.98 mm. The linear regression is presented in Figure 3.

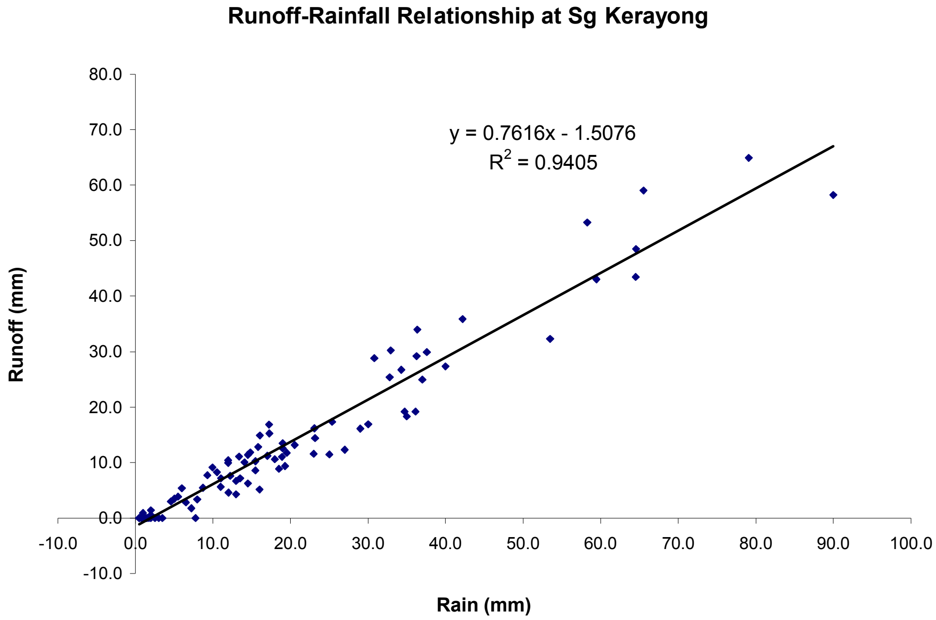

Figure 3: Rainfall-runoff relationship at Sungai Kerayong, Kuala Lumpur.

In comparison with the percentage of impervious surface calculated from the land use map in Table 2, the difference is small, which is only by 1.7%. The results suggest that the impervious surface obtained by regression and land use map technique were quite close. Therefore the regression method can be used for future development planning in the Sungai Kerayong catchment area. The estimated value for depression storage of 1.98 mm is within the typical values used for hydrological modeling using SWMM5, between 1.27mm to 2.54mm for impervious surface. Abustan (1997) also used similar method to estimate the depression storage in Centennial Park, Australia. The estimated impervious area for the catchment was 30% and the depression storage was estimated at 5.5 mm. Generally, this finding has also proven the correlation between the percentage of impervious surface and the depression storage of a catchment, whereby a higher percentage of impervious area will produce low depression storage. Overall, the hydrological properties, namely the impervious surface and the depression storage can be determined from the linear regression of rainfall-runoff events in the catchment.

Estimation of Time of Concentration (t_c)

The time of concentration for the Sungai Kerayong catchment was determined using two different methods. The first method used the direct runoff hydrographs and the second method used four empirical formula to calculate the t_c. The results of both methods are compared to each other.

The runoff generation for the catchment area was calculated by event basis. Twenty direct runoff hydrographs from Taman Desa subcatchment were randomly selected for the estimation of t_c using the first method. As the Taman Desa subcatchment is the outlet for the whole catchment, the t_c is also applicable for the entire catchment. Further investigation shall be carried out by estimating the t_c for the other two sub catchments to examine the t_c behaviours in those areas. The challenge in performing this method is to determine the point of inflection on the recession limb of the hydrograph.

Numerous studies have been conducted in this respect as the recession limb analysis is important for separating individual storm events (Hammond and Han, 2006). Nevertheless, the simple definition as highlighted by McCuen (1989) can be used, whereby the point of inflection is a point in which the hydrograph change from being concave to convex. In this study, the estimate of the inflection point may have encountered error up to 15 minutes. This is likely to happen due to the scale on the time axis (x-axis) is in 15 minutes intervals. However, this method of selecting the inflection point is arbitrary and the results still can be accepted. The summary of time of concentration obtained from 20 direct runoff hydrographs is presented in Table 3.

The t_c estimates for Sungai Kerayong catchment are tabulated in Table 9. From Table 9, the mean t_c was 139 minutes. This value seemed reasonable for a catchment with a size of 48.3km^2. However, to verify this value, the t_c is also estimated by using the empirical formulas. The best equation can be verified by computing the N.S value is summarized in Table 4.

Among the four formulas used, the NAASRA formula showed the best agreement with time of concentration of 141.8 minutes and N.S value of -0.007. The nearest the N.S value to unity indicates an excellent estimation of the t_c. The Bransby-Williams formula gave the poorest agreement with N.S value of -80.795. This clearly suggests that the formula is not suitable to be used for an urban catchment as the formula does not account for the roughness coefficient. As a matter of fact, the roughness coefficient itself represents the type of the catchment and the land use characteristics (e.g. impervious surface). Therefore the formula might be suitable to be used for a natural or rural catchment as proposed by MSMA(DID 2000) and ARR (IEA, 1987).

Compared with the value obtained from the direct runoff hydrograph, the t_c values differ only a little. The mean t_c of 139.5 minutes can be considered acceptable despite only 20 direct runoff hydrographs been analyzed. This result is also in agreement with the NAASRA's formula calculation with small difference of only 1.6%.

Table 3: Summary of t_c estimates for Sungai Kerayong catchment (Taman Desa) from direct runoff hydrographs

Date	Time of Concentration (min)	Rainfall Excess (mm)	Runoff (mm)	Losses (mm)	Losses (%)
July 1, 2001	180	13.4	11.1	2.3	17.0
July 30, 2001	135	8.0	3.4	4.6	57.5
September 30, 2001	150	12.0	9.9	2.0	17.0
October 6, 2001	90	19.0	13.5	5.5	28.9
October 16, 2001	165	14.1	10.1	4.1	28.7
October 28, 2001	120	16.0	14.9	1.1	7.0
November 9, 2001	120	23.2	14.4	8.7	37.7
November 19, 2001	120	37.6	29.9	7.7	20.4
December 1, 2001	165	34.3	26.7	7.6	22.0
February 21, 2002	135	23.1	16.2	6.9	30.1
April 23, 2002	135	42.2	35.9	6.3	15.0
April 27, 2002	90	19.3	9.4	9.9	51.5
May 20, 2002	120	18.9	11.1	7.9	41.5
June 2, 2002	180	36.3	34.0	2.3	6.5
June 16, 2002	120	64.5	48.6	15.9	24.7
October 8, 2002	195	56.1	53.2	2.9	5.2
November 7, 2002	135	65.5	59.0	6.5	9.9
November 13, 2002	150	10.0	9.1	0.9	9.0
January 6, 2003	150	25.3	17.4	8.0	31.5
January 13, 2003	135	4.6	2.9	1.7	37.0
N:	20				
Max:	195				
Min:	90				
Standard Deviation:	27.9991				
Mean:	**139 minutes**				

Table 4: Summary of time of concentration calculated by empirical formula for Taman Desa

Formula	Time of overland flow (t_o)	Time of channel flow (t_{ch})	Time of concentration ($t_c=t_o+t_{ch}$)	N.S value
Yen and Chow	62.9 min	113.2 min	176.1 min	-1.798
NAASRA	**28.6 min**	**113.2 min**	**141.8 min**	**-0.007**
Kerby	37.34 min	113.2 min	150.5 min	-0.162
Bransby- Williams	-	-	384.8 min	-80.795

CONCLUSIONS

This study showed that rainfall and runoff events play important roles in hydrological processes in the catchment. From the land use map, the impervious surface for the catchment was 77.5%. This value is in agreement with the estimated impervious surface from the linear regression of rainfall and runoff. The regression analysis for Sungai Kerayong indicates that the estimate of impervious surface is 76.2% and depression storage of 1.98 mm. By comparing the two results for impervious surface estimations, both methods appear to be acceptable as the difference between the two results is small which is only by 1.7%. The result also suggests that Sungai Kerayong is experiencing rapid urbanization. Despite having used these methods to estimate the impervious surface, the actual value for the impervious surface still needs to be clarified, whereby new formulas or coefficient factors need to be established to solve the issue.

The estimates of the time of concentration (t_c) for the catchment was investigated by using two different approaches. The first approach estimated t_c directly from the direct runoff hydrographs and the second approach used the comparison of formulas. In order to assess the behaviour of t_c, the analysis was divided into three parts which is finding the t_c for the entire catchment area (Taman Desa outlet) and the other two subcatchments, Taman Miharja and Kg. Cheras Baru. The results indicated that the time of concentration for the Sungai Kerayong catchment was 139.5 minutes by the direct runoff hydrograph methods and the NAASRA formula was the best formula with N.S value of -0.007 and the time of concentration of 141.8 minutes. In comparison with the value obtained by the direct runoff hydrographs approach, the difference is only 1.6% and this shows both methods of estimation can be well accepted.

Throughout the analysis, the Bransby-Williams equation has given the poorest statistic agreement for every subcatchments. This suggests that the Bransby-Williams equation is not suitable to be used in highly urbanized catchment areas. Overall, the objectives of this study have been achieved. The rainfall and runoff relationship was successfully developed and the land use characteristics of the catchment have been identified, by assessing the percentage of impervious surface in the catchment area. The times of concentration estimated by several methods were comparable.

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