ESTIMATING THE CLARK INSTANTANEOUS UNIT HYDROGRAPH PARAMETERS FOR SELECTED GAUGED CATCHMENTS IN THE WEST COAST OF PENINSULAR MALAYSIA

Sazali Osman[1] and Ismail Abustan[2]

[1] Department of Irrigation and Drainage Malaysia, Ministry of Water, Land and Natural Resources, Kuala Lumpur, Malaysia, e-mail: sazaliosman@gmail.com

[2] School of Civil Engineering, Universiti Sains Malaysia, Penang, Malaysia, e-mail: ceismail@eng.usm.my

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Abstract

Design hydrographs are important for the design of hydraulic structures such as spillways and retention ponds. Due to the lack of the local data, engineers have to estimate design floods based on techniques which are able to predict runoff based on rainfall on a regional basis. In this study, Clark instantaneous unit hydrographs are used to predict design flood hydrographs for the selected catchments in Pulau Pinang, Perak and Selangor. Recorded rainfall and flood events are used to calibrate the parameters of Clark unit hydrograph model, the time of concentration, *Tc* and storage coefficient, *R*. The efficiency of the model for the calibrated events was measured by Nash and Sutcliffe method. The efficiency for the ten catchments is higher than 0.91 which show good performance of the model for the calibrated events. The parameters are then related to catchment characteristics such as area, main river length and slope of the catchments. The derivation of the empirical equation of Clark unit hydrograph parameters is desirable to identify the model for ungauged catchments in the region. The validity of the equations was tested by using additional storm events and the results show that equations are performing well using the validation datasets. Results show that the Clark instantaneous unit hydrograph model developed in this study can be an effective tool, predicting a reliable hydrograph within study area even though only limited catchments are used.

Keywords: Clark instantaneous unit hydrograph, Design flood hydrographs, Gauged catchments, Unit hydrograph

Introduction

Synthetic unit hydrograph method is widely used in Malaysia and elsewhere for flood analysis. In Malaysia, gauging stations are relatively sparse, especially in the isolated remote region. Records from the gauging stations are unable to provide direct answers to many practical questions in water resources management. Hydrologists and water resources engineers often face this challenge in the course of watershed planning, design of hydraulic structures, hydropower development and dam safety assessments. In this respect, the regional flood estimation and hydrological modeling have become the new approaches to determine design flood. This paper presents the approach to estimate the design flood hydrograph of ungauged catchments in the west coast of Peninsular Malaysia. This approach may be used in practice for the hydrological modeling of ungauged medium size catchments especially the sites which are not located in the gauging stations.

Unit hydrograph method is an established method in relating rainfall-runoff relationship. The concept of unit hydrograph is to transform rainfall excess into direct runoff. Sherman (1932) defined unit hydrograph as “basin outflow resulting from one inch of direct runoff generated uniformly over the drainage area at a uniform rainfall rate during specified period of rainfall duration” [1]. Since the introduction of unit hydrograph by

Sherman, many investigators have developed models for unit hydrograph determination from multi-period rainfall-runoff events. Sherman recommended that the unit hydrograph method should be used for watersheds of 2000 square miles or less. Ponce (1989) proposed unit hydrograph using SCS method for medium size catchments from 100 to 5000 km^2 [2].

Over the years, the event-based rainfall runoff model was reviewed for wider use as more advances techniques are available. Event-based rainfall runoff modeling can be used in determining either the peak flow or the total flow hydrograph [3,4]. Clark (1945) introduced a method to develop synthetic unit hydrograph for use in estimating catchment floods [5]. The Clark unit hydrograph is slightly different from other synthetic unit hydrograph methods; it is an instantaneous unit hydrograph with no duration. The main components of Clark unit hydrograph are: a hydrograph translation and linear reservoir routing. Clark used two parameters (the time of concentration Tc and a storage attenuation coefficient R) and a time-area diagrams which to estimate the unit hydrograph of a catchment [5]. The time of concentration, Tc is the travel time of a drop of water from the most upstream point in the catchment to the outlet location. Clark also described that R is equal to discharge at point of inflection on observed hydrograph divided by the slope at that point. For ungauged catchments, these are estimated using recorded data of adjacent catchments. This can be generated by analyzing physical characteristics using parameter regionalization. Each hydrograph varies in shape, therefore different values can be obtained from different hydrographs and often the simulated hydrographs, based on average value of storage coefficient R, do not fit well with the observed hydrographs.

Study Area

The area selected for this study is located in a central part of west coast Peninsular Malaysia within longitude of 101º 30' 34"E - 101º 31" 43'E, latitude 3º 23' 15"N - 5º 25' 24"N. Ten catchments of five river basins in state of Pulau Pinang, southern part of Kedah, Perak and North Eastern part of Selangor have been selected. The river basins are Perai River basin, Kerian River Basin, Perak River Basin, Bernam River Basin and Selangor River Basin. The catchments cover one district in Pulau Pinang and Kedah which are Seberang Perai Tengah and Kulim, respectively, three districts in Perak which are Selama, Kinta, Batang Padang and two districts in Selangor which are Hulu Selangor and Gombak. The location of streamflow stations and details for each stations are shown in Table 1 and Figure 1, respectively. The climate is generally uniform throughout the study area. The area is generally warm and humid with high temperature and high humidity with relatively small seasonal variation. The mean relative humidity is 77%, while daily minimum and maximum temperatures are 26^oC and 32^oC, respectively. The mean annual rainfall varies from 1600 mm to 3000 mm. The mean annual evaporation ranges from 1200 mm to 1650 mm. The wet seasons occur in April-May and October-November. Dry months generally fall in February-March and June-August.

Table 1. List of Streamflow Stations in Study Area

No.	Station ID	Catchment	Latitude	Longitude	Years of Record (Autographic)	Number of Rainfall Gauge
1	5405421	Sg. Kulim at Ara Kuda	$05^{o}\ 26^{o}\ 06^{o}$	$100^{o}\ 30^{o}\ 44^{o}$	48	4
2	5206432	Sg. Krian at Selama	$05^{o}\ 13^{o}\ 42^{o}$	$100^{o}\ 41^{o}\ 13^{o}$	47	4
3	4511468	Sg. Raia at Keramat Pulai	$04^{o}\ 32^{o}\ 01^{o}$	$101^{o}\ 08^{o}\ 14^{o}$	21	3
4	4311464	Sg. Kampar at Kg. Lanjut	$04^{o}\ 20^{o}\ 10^{o}$	$101^{o}\ 05^{o}\ 58^{o}$	27	4
5	4012401	Sg. Bidor at Malayan Tin Bhd	$04^{o}\ 04^{o}\ 30^{o}$	$101^{o}\ 14^{o}\ 44^{o}$	22	2
6	3913458	Sg. Sungkai at Sungkai	$03^{o}\ 59^{o}\ 28^{o}$	$101^{o}\ 18^{o}\ 49^{o}$	48	2
7	3814416	Sg. Slim at Slim River	$03^{o}\ 49^{o}\ 36^{o}$	$101^{o}\ 24^{o}\ 32^{o}$	43	2
8	3615412	Sg. Bernam at Tg. Malim	$03^{o}\ 40^{o}\ 41^{o}$	$101^{o}\ 31^{o}\ 17^{o}$	50	4
9	3516422	Sg. Selangor at Rasa	$03^{o}\ 30^{o}\ 26^{o}$	$100^{o}\ 38^{o}\ 01^{o}$	39	2
10	3414421	Sg. Selangor at R. Panjang	$03^{o}\ 24^{o}\ 08^{o}$	$100^{o}\ 26^{o}\ 30^{o}$	50	3

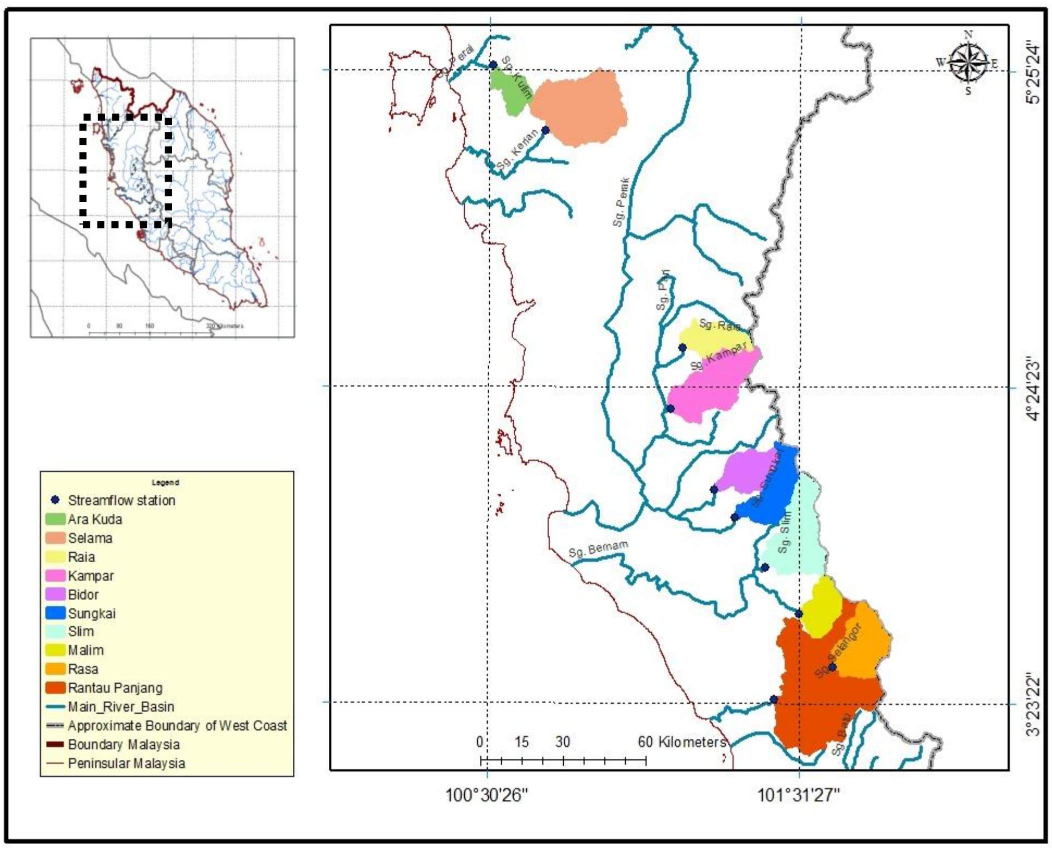


Figure 1. Map of the study area includes streamflow stations

The catchments in the study area are rural catchments and generally characterized by steep rugged mountainous terrain along the main range of Peninsular Malaysia. The river passes through hilly terrain and in the lower reaches and meanders along the flat coastal plain. Themountainous areas consist of forest reserves and the hilly terrains are cultivated while the lower reaches are predominantly swampy areas.

Clark Unit Hydrograph Model

Short term storage of water throughout the catchment in the soil, on the surface and in the channels plays an important role in the transformation of rainfall excess to runoff. The linear reservoir model is a common representation of the effects of this storage. With Clark unit hydrograph model, the linear reservoir represents the aggregated impacts of all catchment storage. Thus conceptually, the reservoir may be considered to be located at the catchment outlet [6].

The Clark unit hydrograph incorporated in HEC-HMS is used for this study. Clark's model derives a catchment unit hydrograph by explicitly representing two critical processes in the transformation of rainfall excess to runoff [6];

- Translation or movement of the rainfall excess from its origin throughout the drainage to the catchment outlet
- Attenuation or reduction of the magnitude of the discharge as the rainfall excess is stored through the catchment

Transformation of rainfall excess to runoff using the Clark unit hydrograph is based on the method of convolution. This method convolves rainfall excess increments with the unit hydrograph ordinates to determine the catchment hydrograph,

$$Q_n = \sum P_m{}^{*} U_{n-m+1} \quad (1)$$

where Q = direct runoffP = rainfall excess depth
U = unit hydrograph ordinates
n = the number of runoff steps
m = the number of rainfall excess steps
as m from 1 to n.

Time of concentration for the catchment is based on time-area concept in which catchment storage effects are taken into account. Clark model accounts for the time required for water to move to the catchment outlet. It does that with a linear channel model in which water is route from the remote points to the linear reservoir at the outlet with delay (translation) but without attenuation [7]. This delay is represented implicitly with that so called time-area histogram. This specifies the catchment area contributing to flow at the outlet as a function of time. If the area is multiplied by unit depth and divided by Δt , the computation time step, the result is inflow, I_t , to the linear reservoir. The typical time-area relationship which is used in HEC-HMS:

$$\frac{A_t}{A} = \begin{cases} 1.414\left(\frac{t}{tc}\right)^{1.5} & for \quad t \le \frac{tc}{2} \\ 1-1.414\left(1-\frac{t}{tc}\right)^{1.5} & for \quad t \ge \frac{tc}{2} \end{cases} \quad (2)$$

where A_t = cumulative catchment area contributing at time t
A = total catchment area
t_c = time of concentration of catchment
as $tc/2 < t < tc$

A study in Hydrologic Engineering Center (HEC) shows that a smooth function filled to a typical time area relationship represents the temporal distribution adequately for unit hydrograph derivation for most catchments [6].

The catchment storage, R is an index of the temporary storage of rainfall excess in the catchments as it drains to the outlet point. It means R accounts for both translation and attenuation of direct runoff hydrograph. It can also be estimated via calibration of model using gauged rainfall and streamflow data. Though R has unit of time, there is only a qualitative meaning for it in the physical sense. Clark indicated that R can be computed as the flow at the inflection point on the falling limb of the hydrograph divided by the time derivative of flow [5]. The translation hydrograph is routed using the continuity equation,

$$\frac{ds}{dt} = I_t - O_t \tag{3}$$

where $\frac{ds}{dt}$ = time rate of the change in water storage at time t.

I_t = average inflow to storage at time t.

O_t = outflow from storage at time t.

For a linear reservoir model, the storage and outflow relationship is

$$S_t = RO_t \tag{4}$$

where S_t = storage at time t

Using finite difference, the outflow from storage can be defined as

$$O(t) = [(\Delta t/(R+0.5\Delta t))*I(t)] + [(1-(\Delta t/(R+0.5\Delta t)))*O(t\text{-}1)] \tag{5}$$

where $O(t)$ = outflow from storage at time t

Δt = time increment

R = storage coefficient

$I(t)$ = average inflow to storage at time t

$O(t\text{-}1)$= outflow from storage at previous time t-1

Methodology

The derivation of the Clark unit hydrograph parameters can be performed manually or with computer model. Because of the difficulty in determining the time-area diagram and to estimate the R parameter consistently, the HEC-HMS model is used in this study. Hydrologic Engineering Center's Hydrologic Modeling Software (HEC-HMS) version 3.3, developed by the US Army Corps Engineers, is designed to simulate the rainfall-runoff processes of catchments system. HEC-HMS allows the modeler to choose between numerous runoff parameterizations [8]. Catchment parameters such as loss parameter, time of concentration, storage coefficient and base flow may need some 'fine tune' to produce a best fit between simulated and observed values. For this study, initial and constant loss model and base flow recession constant are chosen according to the records of particular catchment. The model will optimize the parameters so that the simulated hydrograph will closely match with the observed hydrograph. Figure 2 shows a flow chart of methodology of this study.

The following sections present the fundamental steps in the derivation of equations for time of concentration, *Tc* and storage coefficient, R of Clark model.

Digitization of Catchments Map and Data Processing

ArcGIS version 9.3 developed by Environmental Systems Research Institute (ESRI) are used for delineating the catchment areas, estimating the main river length and slope. Topographic characteristics have a strong influence on runoff velocity, direction and concentration. Catchment area, main river length and slope are probably the most widely used as topographic indices. Traditionally, catchment parameters were extracted from topographic maps manually and it is time consuming and subjected to error. With the advent of digital systems, digital elevation models (DEM) is used for extracting the catchments information such as catchment area, main river length and slope. The catchment area of the particular outlet location can be delineated in fast and accurate as it highly depend on the accuracy of DEM data. GIS software perhaps can increase the accuracy of the results and in the same time reduces the time for extracting the information.

The stream slope adopted for this study is defined as the weighted sum of the incremental slope between successive stream contours [9].

$$S = \left[\frac{\sum_{i=1}^{m} li \times \sqrt{si}}{\sum_{i=1}^{m} li} \right]^2 \tag{6}$$

Where S = Stream slope
li = incremental main stream length and
si = incremental mean stream slope.

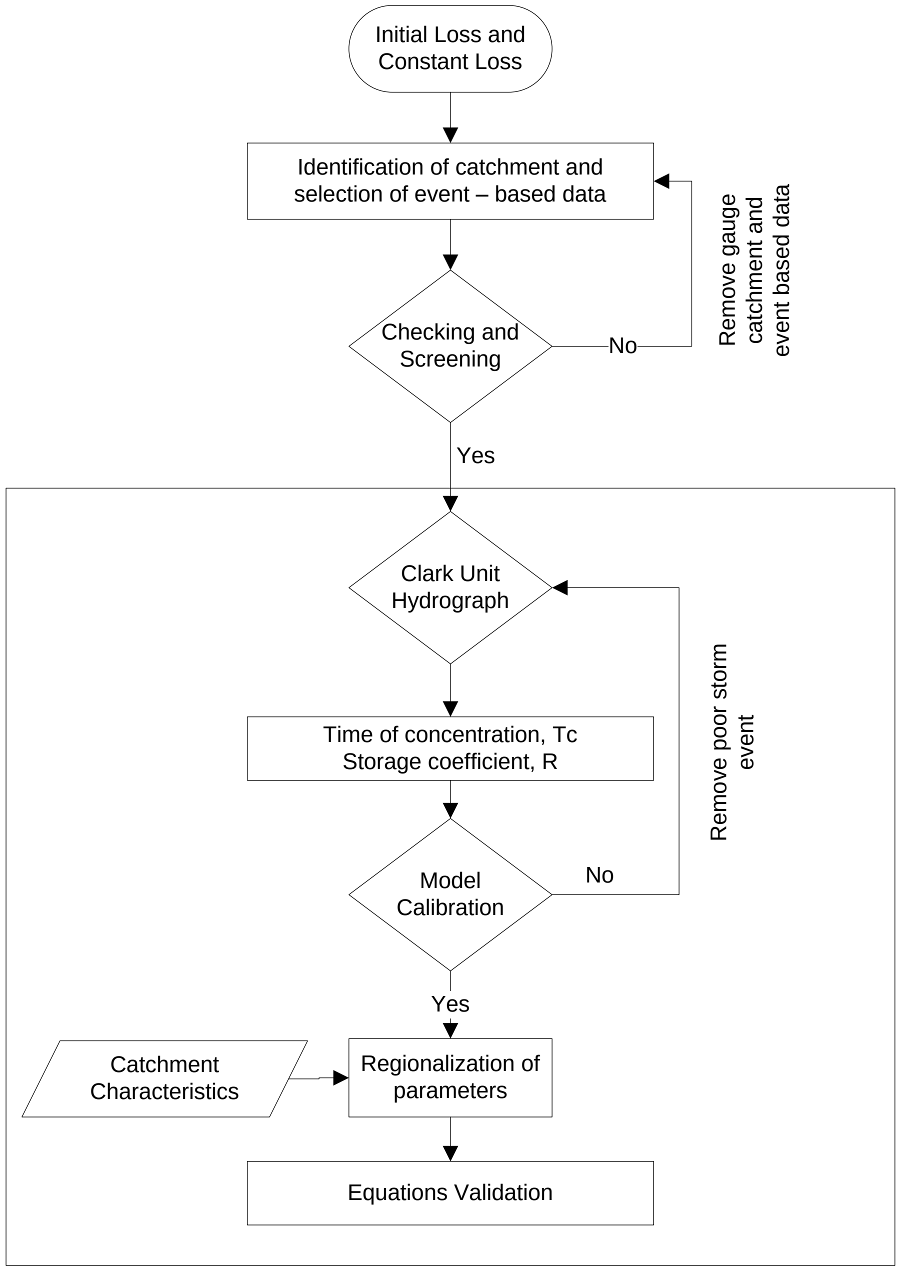


Figure 2. Flow chart the methodology of development Clark unit hydrograph equations

Consistency of Rainfall and Stream Flow Data

Department of Irrigation and Drainage (DID), Malaysia is the main agency which is responsible in managing and publishing hydrologic data. The rainfall and runoff data were obtained from DID. For a study of this scale, a large number of rainfall and stream flow data are used for analysis. The quality of the data is important to ensure good identification of the model as it depends heavily on the data used. A vigorous check for a large volume of data is very tedious work and time consuming. Therefore, consistency check was carried out for the rainfall and stream flow time series data to be used for calibration. The accuracy of rainfall records can be checked using daily rainfall data. Accuracy of rainfall of short duration which is of only a few hours can be screened using the concurrent rainfall records of adjacent stations. This is to ensure that no unusual records are used.

Current meter measurement records and the rating curves are most important to screen the consistency of stream flow records. The flows measured directly will be useful not only in the plotting of rating curves; they are also valuable in comparing the change in river conditions. Extrapolation of rating curve is possible using the flow records in adjacent years if the river conditions do not change much. A check of the consistency of time series data is to rule out outliers such as high flows that do not belong from the same population, persisting high or low peak flows for a long period comparing to the rest of the years.

Calibration of Clark Unit Hydrograph Parameters

The single peak of hydrograph is used for calibration while the rainfall input is obtained from the single storm where the catchment rainfall was calculated using the Thiessen polygon method. Selected recorded rainfall-runoff events for particular catchment have been used to calibrate the Clark method. i.e. to obtain *Tc* and *R*. The Clark parameters were calibrated via automatic optimization. Optimization is terminated after the error between the observed and simulated values of runoff is minimized. Clark parameters are regionalized for use for ungauged catchments. The *Tc* and *R* also are presented in equation form by correlating them to catchments characteristics. The validation of these equations can be done by evaluating the values from average *Tc* and *R* for storm events used for validation and comparing the values from derive equations [10].

Performance of the model calibration and validation were measured by means of its model-fit efficiency, *EFF* from Nash-Sutcliffe equation or coefficient of determination, r^2. The equation also use for measuring the performance of empirical equation [11]. Value of *EFF* is given by the following equation:

$$EFF = \frac{\sum_{i=1}^{n}(Qm_i - Qm)^2 - \sum_{i=1}^{n}\left(Qm_i - Qs_i\right)^2}{\sum_{i=1}^{n}(Qm_i - Qm)^2} \tag{7}$$

where *EFF* = coefficient of efficiency
Qm_i = measured direct runoff at time i
Qm = average measured direct runoff for the storm
Qs_i = simulated direct runoff at time i
n = number of simulated hydrograph ordinates

Result and Discussion

Catchment Characterization

In order to use the Clark method to derive the synthetic unit hydrograph for ungauged catchments, the estimation of Tc and R from the catchment characteristics is required. As discussed by Baron et. al. (1980), the conversion of flood runoff on the catchment surface to the flood hydrograph at the outlet depends largely on the morphological characteristics of the catchment [12]. The catchment shape is a dimensionless factor that measured the shape between narrow or rounded catchment. There is no maximum value for catchment shape, comparison of two catchment shape values for two catchments to reflect the shape of one catchment to other catchments. Larger values indicate more rounded basins while smaller values indicate more narrow basins. For example, Sg. Sungkai at Sungkai has a lower value than Sg. Selangor at Rasa even though both locations have an almost similar catchment area. This indicates that Sg. Sungkai catchment narrower than Sg. Selangor catchment. These factors affect the accuracy of the correlation between the Clark parameters and the catchment characteristics. The characteristics of catchments in the study area are shown in Table 2.

Table 2. Characteristics of Catchments in Study Area

Catchment	Catchment Area, *A*	Main River Length, *L*	Main River Slope, *S* (weighted sum)	Catchment Shape[a]
	(km^2)	(km)	(m/km)	
Sg. Kulim at Ara Kuda	130	30.12	6.72	0.14
Sg. Kerian at Selama	631	46.70	12.37	0.29
Sg. Raia at Keramat Pulai	190	37.81	33.82	0.13
Sg. Kampar at Kg. Lanjut	446	54.71	18.90	0.15
Sg. Bidor at Malayan Tin Berhad	210	34.59	21.11	0.18
Sg. Sungkai at Sungkai	289	44.57	19.72	0.15
Sg. Slim at Slim River	455	50.85	16.10	0.18
Sg. Bernam at Tg. Malim	186	25.41	45.77	0.29
Sg. Selangor at Rasa	322	37.82	23.91	0.23
Sg. Selangor at Rantau Panjang	1450	75.14	8.27	0.26

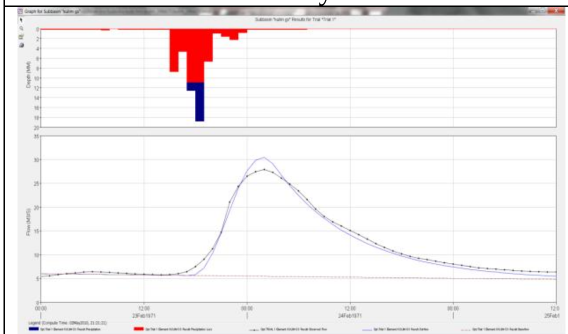
[a] Catchment shape is a dimensionless value that is computed by dividing the catchment area and the square of the main river length (A/L^2)

Calibration of Clark Model and Equation Development

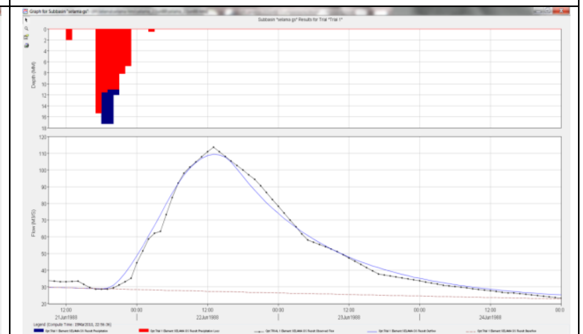
In this study, 126 storms from catchments less than 1500 km^2 throughout study area were calibrated. Out of these, 106 storms were taken from the period 1970 - 2000 and the remaining from 2001 - 2009. The records prior to 2001 were used for developing the Clark equations and the records of 2001-2009 were mainly used to validate the derived Clark equations.

The *Tc* and *R* values for the Clark unit hydrograph method were determined by calibrating HEC-HMS model [8]. Figure 3 shows the sample of calibration hydrograph of rainfall-runoff modeling via optimization technique. Model parameters for losses, baseflow and Clark parameters have been optimized after a few times of trial run during calibration.

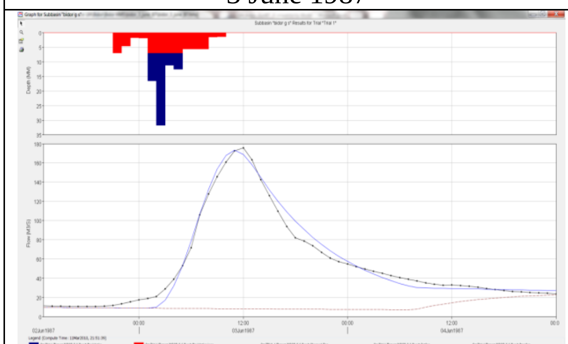
Sg. Kulim at Ara Kuda – 24 February 1971



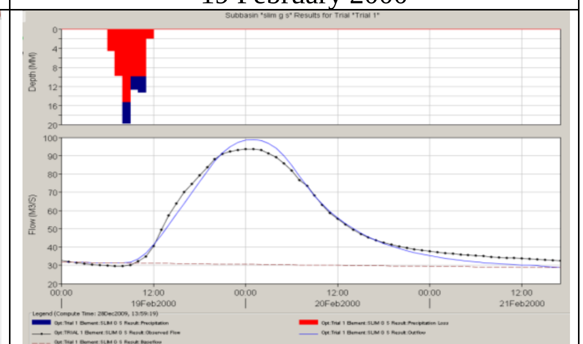
Sg. Krian at Selama – 22 June 1988



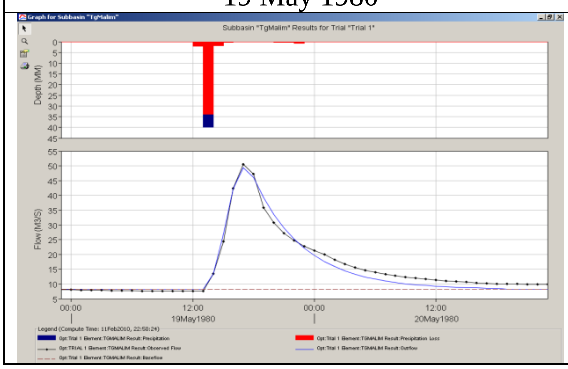
Sg. Bidor at Malayan Tin Bhd – 3 June 1987



Sg. Slim at Slim River – 19 February 2000



Sg. Bernam at Tg. Malim – 19 May 1980



Sg. Selangor at R. Panjang – 5 November 1988

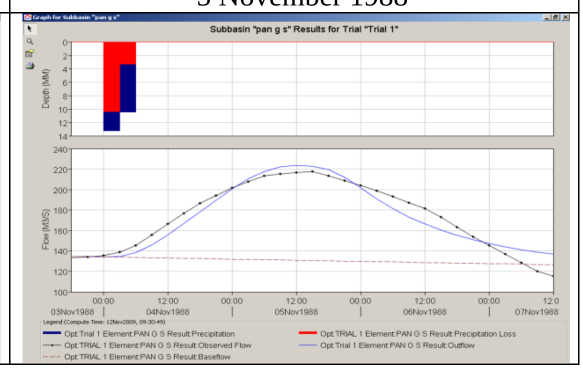


Figure 3. Typical sample of calibration hydrograph using HEC-HMS

The calibration results of time of concentration and storage coefficient for the study catchments used in developing the equations and validations are shown in Table 3 and Table 4, respectively. The calibration results shows model-fit efficiency for ten catchments used for development of the equations and five catchments used for equations validation produces values greater than 0.910 and 0.951, respectively. These generally indicate the calibrated model has successfully reproduces the observed direct runoff hydrograph. From this result it is clear that the use of built-in synthetic time-area diagram of HEC-HMS yields acceptable results of Tc and R so that processing time is reduced. Meanwhile, percentage errors in simulated peak discharge were less than 10 percent between observed and simulated direct runoff hydrograph. It shows the calibrated model has a good performance in simulating the peak discharges for small and moderate catchment size.

Some catchment produces good simulated peak discharge but lower value for EFF and vice versa. This behavior occurs since the model optimization will adjust the simulated discharge by ensuring the volume of simulated direct runoff are equal with the depth of rainfall excess. Therefore, the simulated direct runoff hydrograph that acceptable in term of shape and peak discharge were produced. For example, Sg. Selangor at R. Panjang give good values of simulated peak discharge but lower values of EFF. It may occur due to the effect of catchment size where the large catchment size significantly influenced rainfall spatial distribution that lead to more difficult to produced better hydrograph simulation.

Table 3. Calibration Results of Time of Concentration and Storage Coefficient with the Values of Performance Indicator for All Storms Used for Develop Equations

Catchment	Number of Storms for Equation Development	Time of Concentration (hrs)	Storage Coefficient (hrs)	Error in Simulated Peak Discharge (percent)	Model Fit Efficiency (*EFF*)
Sg. Kulim at Ara Kuda	13	9.82	9.06	2.78	0.962
Sg. Krian at Selama	6	24.65	19.69	-0.63	0.954
Sg. Raia at Keramat Pulai	15	6.00	6.33	-0.98	0.936
Sg. Kampar at Kg. Lanjut	7	9.33	17.69	5.93	0.961
Sg. Bidor at Malayan Tin Bhd	10	7.99	8.97	2.69	0.954
Sg. Sungkai at Sungkai	13	13.02	8.11	1.58	0.958
Sg. Slim at Slim River	23	17.19	8.42	2.63	0.962
Sg. Bernam at Tg. Malim	9	5.12	5.44	2.39	0.956
Sg. Selangor at Rasa	5	6.11	7.83	2.37	0.943
Sg. Selangor at R. Panjang	5	47.75	30.99	0.86	0.910

Table 4. Calibration Results of Time of Concentration and Storage Coefficient with the Values of Performance Indicator for All Storms Used for Validation.

Catchment	Number of Storms for Equation Validation	Time of Concentration (hrs)	Storage Coefficient (hrs)	Error in Simulated Peak Discharge (percent)	Model Fit Efficiency (*EFF*)
Sg. Kulim at Ara Kuda	5	7.17	7.51	5.83	0.967
Sg. Krian at Selama	2	16.25	22.75	9.57	0.958
Sg. Sungkai at Sungkai	1	14.15	8.36	-3.14	0.966
Sg. Slim at Slim River	3	16.64	10.29	7.09	0.973
Sg. Bernam at Tg. Malim	9	3.85	5.16	3.17	0.951

The time of concentration and storage coefficient has been regionalized using the catchment characteristics. Three catchment characteristics, catchment area, main river length and main river slope are related to the Clark parameters using multiple linear regression and the following equations have been developed;

$$Tc = 0.4444\, A^{0.4867}\, (L/S)^{0.4868} \qquad r^2 = 0.88 \tag{8}$$

$$R = 1.2930\, A^{0.5434}\, S^{-0.3689} \qquad r^2 = 0.85 \tag{9}$$

Validation of Equations

To check the reliability of the equations (8) and (9), five catchments consisting 20 storm events were used to estimate the Clark unit hydrograph parameters. The calibrated values of time of concentration and storage coefficient for validation storms are shown in Table 4. Basically these catchments used in validation are part of the catchments used in developing the equations. Storms used in validation generally are from the periods 2001 to 2009. The selection of the periods for validation storms are differ than storms used for equations development in respect to examine the reliability and consistency of the equations. The validations have not carried out for another five catchments since some catchments such as Sg. Selangor at Rantau Panjang and Sg. Selangor at Rasa significantly affected by the regulating dams in which operated after the year 2000. Meanwhile the others three catchments have a short period of data which mean no data for the periods of 2001 to 2009.

Table 5. Comparison of Time of Concentration Estimated with Equations Developed in This Study and with Values Determined from Model Optimization

Catchment	*Tc* Estimated from Equation	*Tc* Determined from Model Optimization (Calibration)	*Tc* Determined from Model Optimization (Validation)	Percentage Relative Error (Calibration)	Percentage Relative Error (Validation)
Sg. Kulim at Ara Kuda	9.86	9.82	7.17	-0.41	-37.52
Sg. Krian at Selama	19.57	24.65	16.25	20.61	-20.43
Sg. Sungkai at Sungkai	10.42	13.02	14.15	19.97	26.36
Sg. Slim at Slim River	15.30	17.19	16.64	10.99	8.05
Sg. Bernam at Tg. Malim	4.25	5.12	3.85	16.99	-10.39
Average				13.63	-6.78

Table 6. Comparison of Storage Coefficient Estimated with Equations Developed in This Study and with Values Determined from Model Optimization

Catchment	*R* Estimated from Equation	*R* Determined from Model Optimization (Calibration)	R Determined from Model Optimization (Validation)	Percentage Relative Error (Calibration)	Percentage Relative Error (Validation)
Sg. Kulim at Ara Kuda	9.02	9.06	7.51	0.44	-20.11
Sg. Krian at Selama	16.99	19.69	22.75	13.71	25.32
Sg. Sungkai at Sungkai	9.36	8.11	8.36	-15.41	-11.96
Sg. Slim at Slim River	12.91	8.42	10.29	-53.33	-25.46
Sg. Bernam at Tg. Malim	5.40	5.44	5.16	0.74	-4.65
Average				-10.77	-7.37

Table 5 and Table 6 show a comparison of results for Clark unit hydrograph parameters, time of concentration and storage coefficient, respectively, which are calculated using the equations developed in this study with the values determined from model optimization for storm used in equations development (calibration) and equations validation. It can be seen that the time of concentration calculated using the equation has a good performance compared to the values from storm calibration and storm validation. The percentage error of time of concentration more consistent for calibration storms compared to validation storms. It is true because these empirical equations were developed based on calibration storms. The performance of storage coefficient parameter estimated from equation is generally better than time of concentration. However, Sg. Slim at Slim River produces slightly high percentage of relative error for calibration storms. It may occur due to the effect of regionalization during the development of equations. Based on the Equation (9), the independent variables used are catchment area and main river slope. The values of calibrated storage coefficient for Sg. Slim ar Slim River were small compared to the other catchments which have similar catchment area. It means Sg. Slim at Slim River catchment not significantly influenced by storage effect. Results are also plotted in Figure 7 and Figure 8. In the figures, *Tc* and *R* from both the calibration and validation storms are plotted against those derives from the equations, seen from the figures that for most of the catchments, the difference between the points plotted using validation storms and the equation and that plotted using calibration storms and the equation is not significant.

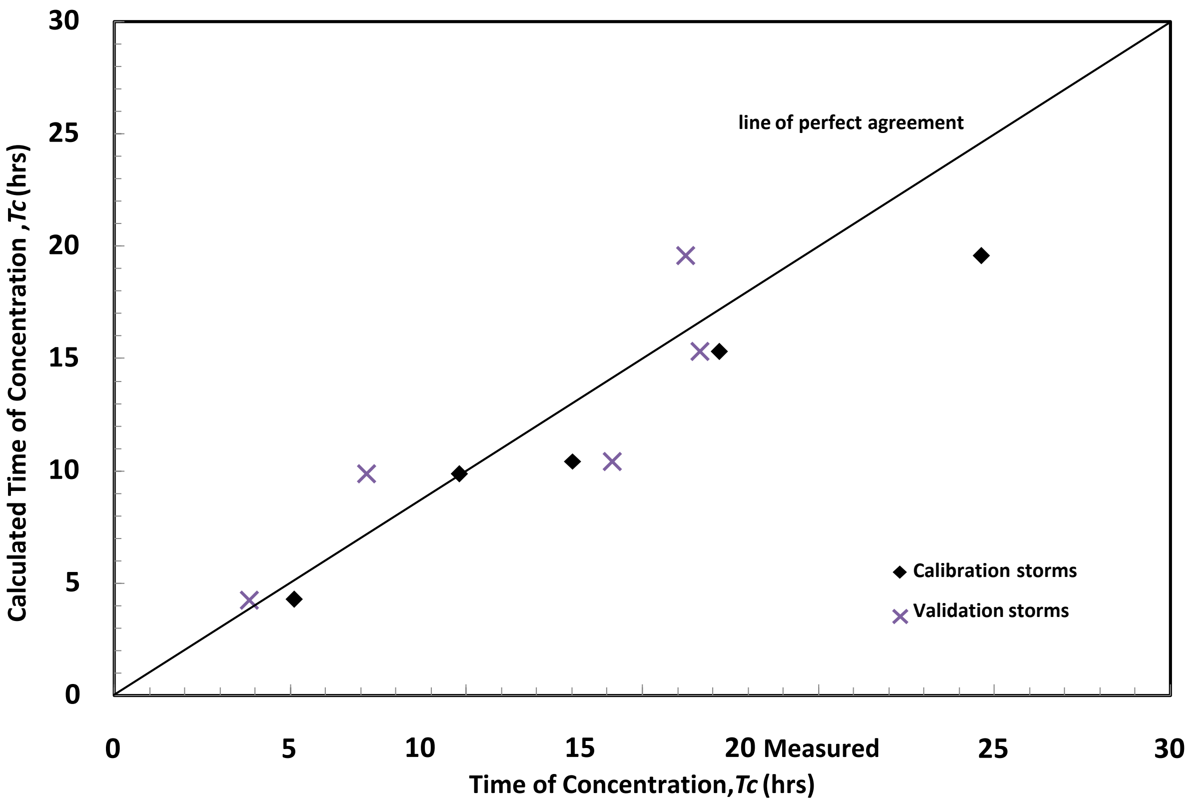


Figure 7. Time of concentration between calculated and measured used for calibration and validation

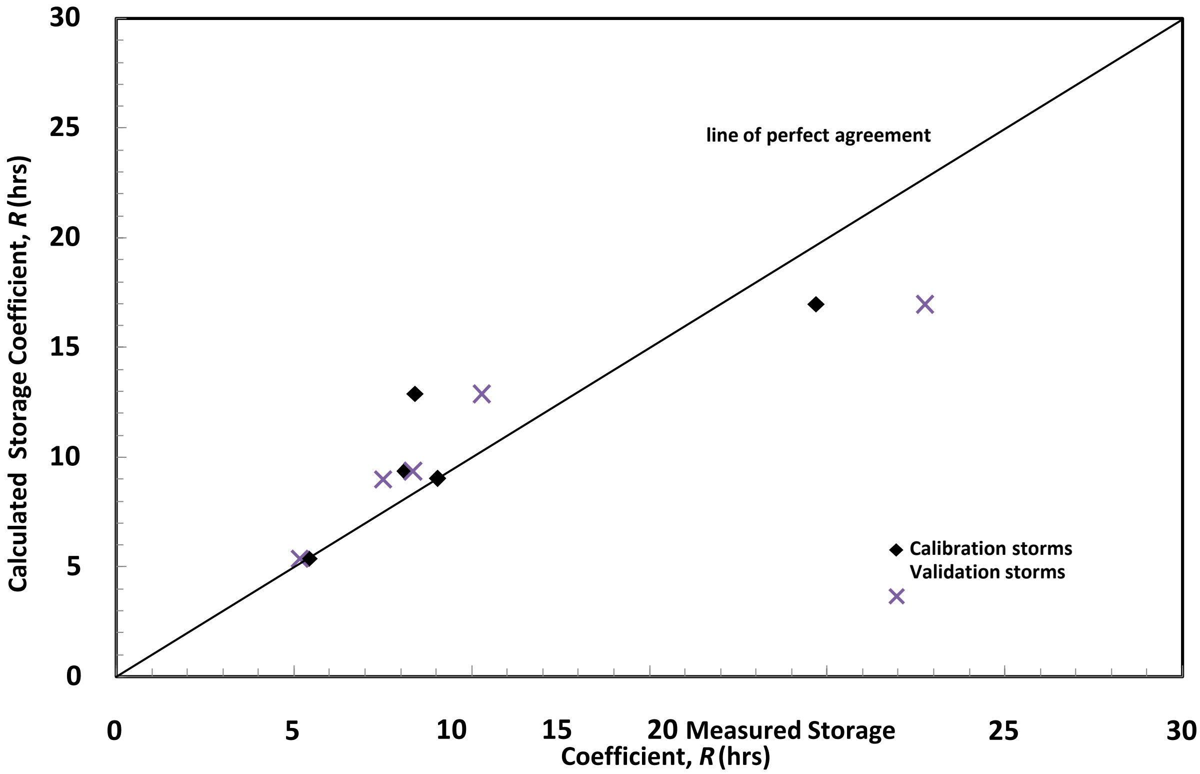


Figure 8. Storage coefficient between calculated and measured used for calibration and validation

Additionally, the equations were tested using the storm events which are used in the validation process. HEC-HMS model is used to simulate the hydrographs using Equations (8) and (9). The comparison of the simulation results are shown in Table 7. Results are acceptable because the percentage error in peak discharge between observed and simulated is generally less than 30%. The model fit efficiency also shows a good results for 15 storm events which have a values larger than 0.80. Meanwhile 4 events have model fit efficiency more than 0.70. Although the equations developed using calibrated Clark unit hydrograph parameter for the catchment size between 130 – 1450 km^2, the validation is performed only for the catchment size between 130 – 631 km2. Therefore, the equations were reliable to be used for catchment area less than 631 km^2.

Table 7. Comparison of the Percentage Error in the Observed and Simulated Peak Discharge for the Storms Used in Validation of Develop Equations

Catchment	Date of Storm	Peak Discharge (Observed)	Peak Discharge (Simulated)	Error in Peak Discharge	Model-Fit-Efficiency (*EFF*)
		(m^3/s)	(m^3/s)	(%)	
Sg. Kulim at Ara Kuda	20-Oct-05	48.50	36.17	-25.42	0.627
	18-Sep-05	49.61	41.21	-16.93	0.720
	29-Mar-05	51.02	35.02	-31.36	0.739
	2-Nov-04	49.44	45.42	-8.13	0.848
	8-Sep-03	50.18	61.54	22.64	0.962
Sg. Krian at Selama	30-May-09	104.52	123.73	18.38	0.902
	8-Sep-07	144.63	180.86	25.05	0.870
Sg. Sungkai at Sungkai	7-May-02	44.00	46.78	6.32	0.868
Sg. Slim at Slim River	28-Apr-07	48.31	47.16	-2.38	0.945
	2-Oct-03	52.40	61.34	17.06	0.889
	8-May-01	80.80	74.54	-7.75	0.871
Sg. Bernam at Tg. Malim	1-Sep-09	78.16	66.02	-15.53	0.932
	8-Jun-08	124.64	100.54	-19.34	0.913
	16-Apr-07	106.80	84.10	-21.25	0.905
	24-Aug-05	168.05	113.24	-32.62	0.884
	6-Nov-04	126.66	107.40	-15.21	0.768
	11-Nov-03	115.60	101.27	-12.40	0.912
	12-Oct-03	74.96	86.87	15.89	0.889
	25-Sep-03	85.29	94.46	10.75	0.709
	2-May-03	98.87	149.40	51.11	0.743

Conclusions

To obtain the exact values on flood magnitudes and probability of occurring is a challenge for the hydrologist. No one method (empirical, deterministic and probabilistic) can be accepted as better than the other, as all methods are approximations and their accuracy is relative. The results of this study show that the Clark unit hydrograph parameter is a reliable tool to estimate peak discharges for tropical climate conditions.

The applications of the derived Clark equations were limited to the range of catchment area, main river length and slope used in deriving the equations. Since the equations validations perform for limited catchment, the equations are recommended for used in sites that have catchment area smaller than 631 km^2. The equations derived in this study can be further used in other areas by conditions, with more catchments and more calibrated parameters to be included in deriving the equations. The methods shall also be used for a smaller catchment especially in the urban area to provide a more reliable and useful relationship in conditions the parameters must be well calibrated.

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