Methods of Estimating Time of Concentration: A Case Study of Urban Catchment of Sungai Kerayong, Kuala Lumpur

Rofiat Bunmi Mudashiru, Ismail Abustan and Fauzi Baharudin

Abstract Characterization of hydrologic processes of a catchment in relation to water resources structures design requires estimation of time-response characteristics which is used in hydrologic models. The time of concentration (T_c) is an essential component in hydrological modelling which is used in predicting the response time of a catchment to a storm event. There are many approaches in the estimation of time of concentration from literature. At gauged watersheds, T_c can be estimated using rainfall and a runoff hydrograph, while for ungauged catchments, empirical equations are used. In this study, variability of empirical methodologies and hydrograph separation method for evaluating T_c using data from past study on Sungai Kerayong, Kuala Lumpur is presented. Results of the study showed Gundlach, Carter and NAASRA methods are suitable for estimating T_c in the study area while Bransby-Williams and Ventura methods were the poorest in estimation of T_c in the study.

Keywords Hydrological modelling · Empirical method · Hydrograph · Time of concentration

R. B. Mudashiru (✉)
Department of Civil Engineering, Federal Polytechnic Offa,
PMB 420, Offa, Kwara State, Nigeria
e-mail: bunmbello@gmail.com

I. Abustan
School of Civil Engineering, Universiti Sains Malaysia, Engineering Campus,
14300 Nibong Tebal, Pulau Pinang, Malaysia

F. Baharudin
Faculty of Civil Engineering, Universiti Tecknologi MARA, 40450 Shah Alam,
Selangor, Malaysia

F. Mohamed Nazri (ed.), *Proceedings of AICCE'19*, Lecture Notes in Civil Engineering 53, https://doi.org/10.1007/978-3-030-32816-0_8

1 Introduction

Determination of runoff characteristics in a catchment has always been a critical subject in hydrological analysis. The time of concentration (T_c) is a basic catchment response time criteria needed for forecasting of the peak discharge rate and the timing of the flood event [1]. Nearly all hydrologic analyses depend upon one or more time-scale parameters as input. The time of concentration (T_c) is the most commonly used time parameter [2] because it is a key parameter in runoff estimation. Time parameters describe the accumulation of excess rainfall over a watershed and, as such, they have a direct and significant impact on the peak discharge and shape of the hydrograph. Time parameters are linked to the physical characteristics and the morphology of the watershed. Time parameters are an important part of rainfall-runoff hydrologic design and modelling [3]. T_c cannot be defined precisely, and likely differs from season to season and from storm to storm [4]. The time of concentration is the time necessary for water to flow from the remotest part of the outlet once the soil has become saturated and small depressions filled to the watershed outlet. On the other hand, time of concentration t_c can be evaluated from a rainfall hyetograph and the resulting runoff hydrograph. From this perspective, the time of concentration is the time between the centre of mass of rainfall excess and the inflection point on the recession curve of the direct runoff hydrograph [3]. A lot of empirical methods have been developed and used by several authors in estimating the time of concentration in a catchment. Precision in the estimation of T_c is very important to avoid overestimation in peak discharge result and vice versa [5]. Still, modelers are having problems in ascertaining the level of accuracy of these empirical methods. There has been previous effort in evaluating the accuracy of these methods. Nagy et al. [6] found out that Wisnovszky-equation underestimated T_c when they used HEC-HMS to model runoff using T_c as one of the input parameters. Salimi et al. [7] used 22 methods in estimating T_c and applied the values obtained in HEC-HMS. Their findings showed that peak runoff values estimate from Bransby-Williams method were the most consistent and displayed hydrologic condition of the watershed well. Almeida et al. [8] applied hierarchical cluster analysis (Cluster) to 30 empirical methods prioritizing those methods that incorporated rainfall intensity to evaluate the rate of similarity amongst the methods. Pasini's and Ventura's method presented the highest similarity while Arizona DOT (Arizona Department of Transportation) showed strong dissimilarities. Sharifi and Hosseini [2] established that California, Kirpich and Arizona DOT equations performed outstandingly when seven T_c equations were modified to reduce their bias. Almeida et al. [9] used graphical method to analyze T_c and compared the results to the results of T_c obtained using twenty empirical equations from past references. Findings showed that the graphical method was efficient and dependable in determining T_c, and Ventura's equation was outstanding for a rural catchment in a tropical climate region.

Understanding the role of a catchment in relation to T_c is crucial for determining rainfall and peak flow [9]. Substantial errors in peak runoff quantification at catchment scales can be attributed to errors in the estimation of catchment response times like T_c and eventual false estimation of peak runoff [10]. Techniques for estimating time parameters generally need one or more watershed characteristics. For example, a method might require channel length or channel slope [11]. This paper provides in-depth analysis into the variability of accuracy of the various methods used for estimation of T_c for Sungai Kerayong Catchment in Kuala Lumpur, Malaysia. The study will use more referenced empirical methods to estimate value of T_c. The additional methodologies will be explained and results with be compared and discussed.

1.1 Objectives

The main objective of this study is to estimate the value of T_c by using Carter, Johnstone-Cross, Hakatnir-Sezen, Gundlach, revised CUHP (Colorado Urban Hydrograph Procedure), Papadakis-Kazan, Ventura and Arizona DOT methods. The eight methods are used and the results of T_c evaluated was compared to the T_c estimated from direct runoff hydrograph (DRH) for the Sungai Kerayong Catchment in previous study by Abustan et al. [12], Baharudin [13]. In order to evaluate the reliability of the results obtained from the DRHs and the extended empirical formulas, Nash–Sutcliffe efficiency index (NS) method was applied using an objective function.

2 Study Area

Sungai Kerayong catchment is located in Kuala Lumpur of Peninsular Malaysia. It has an area of 48.3 km^2 and consists of four major districts namely Kuala Lumpur, Ampang, Salak Selatan and Pekan Batu Sembilan. The elevation ranges between 30 and 175 m above mean sea level. The study area has year-round equatorial climate which is warm and sunny, along with heavy rainfall, especially during the south-west monsoon from April to September and has a record of 2266 mm mean annual precipitation. Urbanization has been vast throughout the years whereby continuous developments and increased population occurs in the study area. This has made Sungai Kerayong catchment an ideal selection as an experimental urban catchment to monitor the hydrological characteristics and time response parameters of the area. The study area is shown in Fig. 1 and the Stream network and subcatchments are shown in Fig. 2.

Fig. 1 Map of the Sungai Kerayong catchment area

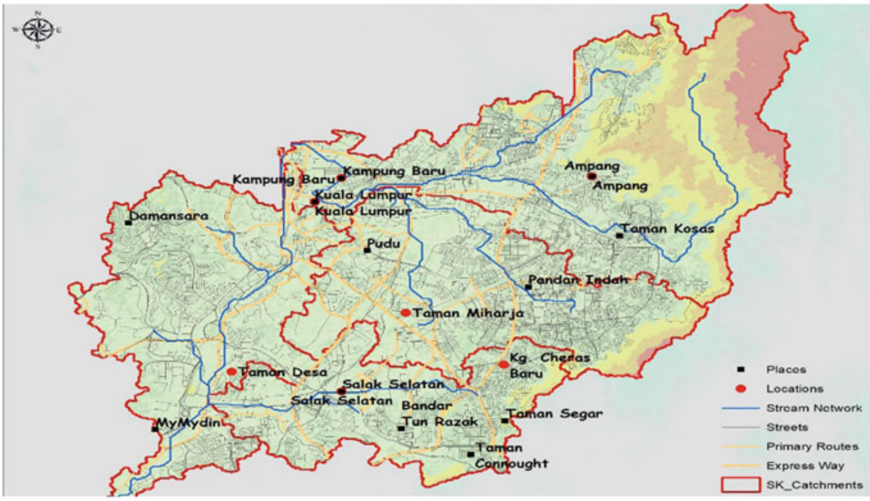

Fig. 2 Stream network and sub catchment map

2.1 Previous Studies

There have been various and extensive studies on T_c estimation. There are two common approaches developed to estimate T_c, first is the velocity-based method [3]. (i) The hydraulics aspect wherein empirical equations that are regression based can be used in the analysis. (ii) The second approach is based on time-lag method where T_c can be computed from time difference between the end of rainfall excess and the inflection point. For this study various empirical methods will be explained and summarized here. A review of study of rainfall-runoff characteristics by Abustan et al. [12], Baharudin [13] for Sungai Kerayong will be conducted and eight more empirical approach will be used for further analysis to check the most suitable method for the study area (Table 1).

Table 1 Summarized empirical methods

References/ equation name	Equation	Remark
Carter [14]	$T_c = 0.0015476L^{0.6}S^{-0.3}$ L = Length of the watershed along the main channel from the hydraulically most distant point to outlet, m S = average slope of watershed, m/m Tc = Time of Concentration, h	Data of an urban basin in the USA (A < 20.72 km^2) and (S < 0.005) [15]. Developed for urban watersheds area less than 20:719 km^2 (8 $mile^2$) Channel length less than 11.26 km (7 mile) [2] Applicable to natural watersheds and partially severed land uses [3]
Chen and Wong [16]	$T_C = \left\{\frac{0.21(K_v)^k CL_o^{2-k}}{Si_n^{1+k}}\right\}$ K = 3.6 × 10^6 v = kinematic viscosity of water, m^2/s L_o = Length of overland plane, m S = Slope of overland plane, m/m C, k = constants (for smooth paved surfaces, C = 3, k = 0.5. For grass, C = 1, k = 0) i = net rainfall intensity, mm/h	Can be applied to small basins with flow regimes from turbulent to laminar [16] Overland flow on test plots of 1 m wide by 25 m long. Slopes of 2 and 5% [7]
NRCS [17]	$T_c = \frac{L^{0.8}\left[\frac{1000}{CN}-9\right]^{0.7}}{441Y^{0.5}}$ T_c = time of concentration, h L = length of mainstream to farthest divide, m Y = average watershed slope, % CN = NRCS curve number	Applicable to small rural catchment of 1–800 ha, rural catchment with a flow length between 60 and 7900 m, and an average watershed slope between 0.5 and 64%
Kirpich [18]	$T_c = \left[\frac{0.948L^3}{H}\right]^{0.385}$ T_c = time of concentration, h L = length of the longest waterway from the point in question to the basin divide, km H = difference in elevation between the point in question and the basin divide (omitting drops due to gully overfills, waterfalls, etc.), m	Works well for a natural, rural basin with well-defined channels, developed for small drainage basins with basin areas of 1–112 acres (0.40–45.3 ha)
Kerby [19]	$T_o = K\left(LNS^{-0.5}\right)^{0.467}$ T_o = time of overland flow, min K = 1.44 L = length of flow, m N = retardance roughness coefficient (see (NRCS)TR 20 Example Problem: Methods for Calculating Time of Concentration) S = average slope of overland flow, decimal	Developed for watershed of less than 4 ha and slope less than 1% Analysis of overland flow in experimental surfaces (L < 0.37 km) [15]

(continued)

Table 1 (continued)

References/ equation name	Equation	Remark
FHWA [20]	$T_o = \frac{6.92L^{0.6}n^{0.6}}{(Ci)^{0.4}S^{0.3}}$ T_o = time of overland flow, min L = overland flow length, m n = Manning roughness coefficient C = runoff coefficient i = rainfall rate, mm/h S = average slope of the overland area, decimal	Analysis of overland flow in experimental surfaces (L < 0.03 km) [15]
Williams [21]	$T_c = 60LA^{0.4}D^{-1}S^{-0.2}$ T_c = time of concentration, m L = basin length, mile A = basin area, mile^2 D = diameter (mile) of a circular basin of area S = basin slope, %	Applicable to basin areas less than 50 mile^2 (129.5 km^2)
Izzard and Hicks [22]	$T_c = 41.025(0.0007i + c)L^{0.33}S^{-0.333}i^{-0.667}$ T_c = time of concentration, m i = rainfall intensity, in./h c = retardance coefficient L = length of flow path, ft S = slope of flow path, ft/ft	Hydraulically derived formula; values of c range from 0.007 for very smooth pavement to 0.012 for concrete pavement to 0.06 for dense turf
Morgali and Linsley [23]	$T_c = 0.94L^{0.6}n^{0.6}S^{-0.3}i^{-0.4}$ L = length of overland flow, ft n = manning roughness coefficient S = average overland slope, ft/ft i = rainfall intensity, in./h	Applicable to small catchment [7]. For small urban areas with drainage areas less than 10 or 12 acres [15]
United States Soil Conservation Service (SCS) [24]	$T_c = {}^1\!/_{60} \sum \left(\frac{L}{V}\right)$ T_c = time of concentration, m L = length of flow path, ft V = average velocity in ft/s for various surfaces (The exponent of S, if converted from Manning's equation, will be −0.5)	Developed as a sum of individual travel times. V can be calculated using Manning's equation
Johnstone and Cross [25]	$T_c = 300L^{0.5}S^{-0.5}$ T_c = time of concentration, h L = basin length, mile S = basin slope, ft/mile Or $T_c = 3.258L^{0.5}S^{-0.5}$ T_c = time of concentration, m L = basin length, km S = basin slope, m/m	Developed for basins with areas between 25 and 1624 mile^2 (64.7 and 4206.1 km^2)
Yen and Chow [26]	$T_o = 1.2\left\{\frac{nL_o}{S_o}\right\}^{0.6}$ T_o = time of overland flow, min L_o = overland flow length, m n = Manning roughness coefficient of overland surface S_o = average slope of the overland area, decimal	Developed for overland flow for small catchments

(continued)

Table 1 (continued)

References/ equation name	Equation	Remark
Bransby [27]	$T_c = \frac{58L}{A^{0.1}S_e^{0.2}}$ T_c = time of concentration, m L_o = overland flow length, m n = Manning roughness coefficient of overland surface S_o = slope of overland plane, m/m	Specially recommended for rural basin [15] Applicable to big catchments [7]
Gundlach [28]	$T_c = 5.69\left[\frac{A}{S_c}\right]^{0.27}(1+30I)^{-0.6}$ A = drainage area of the basin km^2 Sc = slope of the main channel in the direction of flow (m km^{-1}) I = is the fraction of the basin area that is impervious	Applicable to urban catchments [29]
ARR [30]	$T_o = \frac{42.6N_aL_o^{0.333}}{S_o^{0.2}}$ T_o = time of overland flow, min L_o = overland flow length, m N_k = NAASRA retardance coefficient S_o = average slope of the overland area, decimal	Applicable for urban catchments
Haktanir and Sezen [31]	$T_L = 0.2685L_m^{0.841}$ L_m = length of the main channel, in km T_l = is lag time, in h Tc is derived from lag time based on the NRCS relationship T_L = 0.6 Tc [17] Therefore $T_c = 0.4475L_m^{0.841}$	Data of 10 basins in Turkey (10–10,000 km^2) [31]
USDCM [32] CUHP (2005)	$T_{c1} = t_i + t_t$ T_{c1} = computed time of concentration, min t_i = overland (initial) flow time, min t_t = channel flow time, min $t_i = 0.395\frac{[1.1-C_5]\sqrt{L_i}}{S_o^{0.33}}$ t_i = overland (initial) flow time, min C_5 = runoff coefficient for 5-year frequency L_i = length of overland flow, ft S_o = average slope of the overland flow path, ft/ft $t_t = \frac{L_t}{60K\sqrt{S_o}} = \frac{L_t}{60V_t}$ t_t = channel flow time (travel time, min) L_t = waterway length, ft S_o = waterway slope, ft/ft V_t = travel time velocity, ft/s = $K\sqrt{S_o}$ K = NRCS conveyance factor $T_{c2} = (26-17i) + \left\{\frac{L_t}{60(14i+9)\sqrt{S_t}}\right\}$ T_{c2} = minimum time of concentration for first design point when less than T_{c1} L_t = length of channel flow path, ft i = impervious surface % (expressed as a decimal) S_t = slope of the channelized flow path, ft/ft	Adequate for distances up to 300 ft in urban areas and 500 ft in rural areas It was created using the UDFCD database that includes 295 sample urban catchments under 2-, 5-, 10-, 50-, and 100-year storm events [33]. It indicates that both initial flow time and channelized flow velocity are directly related to the catchment's imperviousness [34]

(continued)

Table 1 (continued)

References/ equation name	Equation	Remark
Salimi et al. [7]	$T_c = 7.62\left(A/S\right)^{0.5}$ T_c = time of concentration, min A = surface of the basin, km^2 S = average slope of the hydraulic way, m/m	Applicable to rural basins [7]
ARIZONA DOT [35]	$T_c = 0.0097956A^{0.1}(1000L)^{0.25}L_{ca}^{0.25}S^{-0.2}$ Tc: time of concentration, h L: flow path length, km Lca: mean length starting from the concentration spot along the L up to the spot where L is perpendicular to the centroid of the catchment, m A: catchment area, km^2 S: flow path slope, m/m	Developed from data of agricultural basins [15]
Papadakis and Kazan [36]	$T_c = 0.66L^{0.5}n^{0.52}S^{-0.31}i^{-0.38}$ Tc = time of concentration, min L = length of the longest waterway, ft S = slope of the flow path, % i = intensity of the rainfall excess, in./h n = roughness coefficient (Manning's n value for channel)	Developed from Agricultural Research Service (ARS) data of 84 small rural watersheds from 22 states across the United States [37]
Guo and Urbonas [38] CUHP (2008)	$T_c = t_o + t_f$ t_o = overland flow time, min t_f = channel flow time, min $t_o = 0.395\frac{[1.1-C]\sqrt{L_o}}{S_o^{0.33}}$ t_o = overland flow time, min L_o = overland flow length, ft S_o = overland flow slope, ft/ft $t_f = \frac{L_f}{60K\sqrt{S_f}}$ L_f = channel flow length, ft K = conveyance coefficient, S_f = channel slope, ft/ft, and C = design event's runoff coefficient (i.e., not the runoff coefficient for the 5-year event, C5), in 2001 USDCM $T_R = \frac{L_o + L_f}{180} + 10$ where T_R = regional time of concentration in minutes for catchments with imperviousness greater than 20%	Maximum Tc was found to be only applicable to watersheds with imperviousness less than 20% T_R applicable to Imp > 20% in which TR = regional time of concentration in minutes

3 Materials and Methods

The data used in this study are retrieved from study of rainfall-runoff characteristics of Sungai Kerayong [13]. Rainfall and water level data from Malaysia Department of Irrigation and Drainage (DID) and parameters for cross sections of the channels from channel survey and satellite images for assessing initial condition of channels were used to establish discharge for the storm events using Manning's equation. The study area was delineated into three sub-catchments namely the Kg. Cheras Baru, Taman Miharja and the Taman Desa. A summary of catchment parameters used for T_c estimation is presented in Tables 2 and 3. The elevation map of Sungai Kerayong catchment is shown in Fig. 3. Runoff co-efficient value C of 0.60 was used for the three sub-catchments for revised CUHP because of the level of urbanization of the study area.

Estimation of T_c for the sub-catchments were done after establishing all needed parameters for each equation. Five new empirical equations are selected to evaluate T_c for the study area based on the characteristics of the study area and suitability of the empirical methods relative to their past recommendations. Rainfall intensity of 150 mm/h was adopted for the study from MSMA [39]. The formula T_R was adopted for the revised CUHP as the percentage of impervious surface for the study area was 76.2%.

The previous work by Baharudin [13] used direct runoff hydrographs (DRH) to estimate the time of concentration of the catchments for 20 storm events. The DRH of a storm event for each catchment is shown in Fig. 4 and other storm events are presented in the Appendix.

Table 2 Summary of parameters required for estimation of T_c using empirical equations

Sub-catchment area	Area, km^2	Length of channel, m	Length of overland plane (L_o), m	Slope of overland plane (S_o)	Slope (S_{ch})	Average velocity (V_{avg}), m/s
Kg. Cheras Baru	13.9	2851	2064	0.027	0.0041	3.07
Taman Miharja	13.7	5802	3458	0.00434	0.0045	1.76
Taman Desa	20.7	12021	3458	0.00434	0.0040	1.77

Table 3 Summary of additional parameters required for estimation of T_c using empirical equations

Sub-catchment area	Time of channel flow ($t_{ch} = L_{ch}/V_{avg}$), min	Manning roughness coefficient (n)	Channel flow length (m)	Impervious fraction (I)	Equal area slope of channel, m/km
Kg. Cheras Baru	15.5	0.011	2.437	0.691	2.807
Taman Miharja	54.9	0.035	1.1806	0.787	2.807
Taman Desa	113.2	0.035	0.86099	0.885	2.807

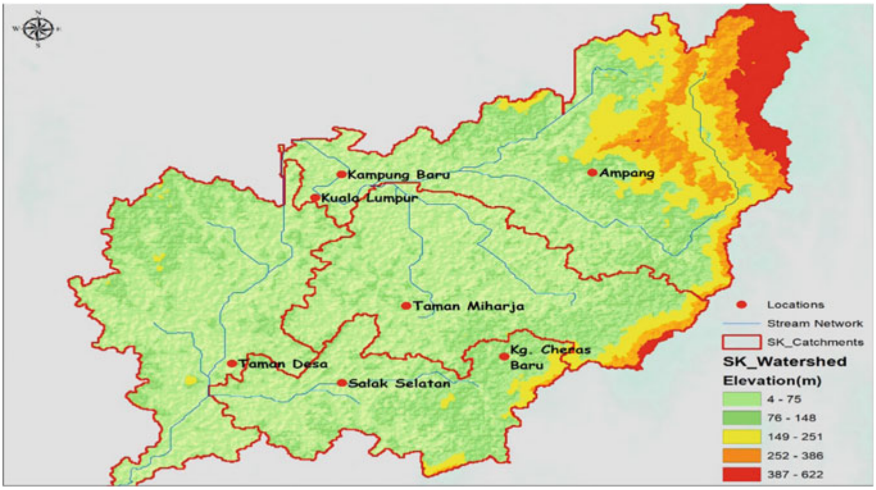

Fig. 3 Elevation map

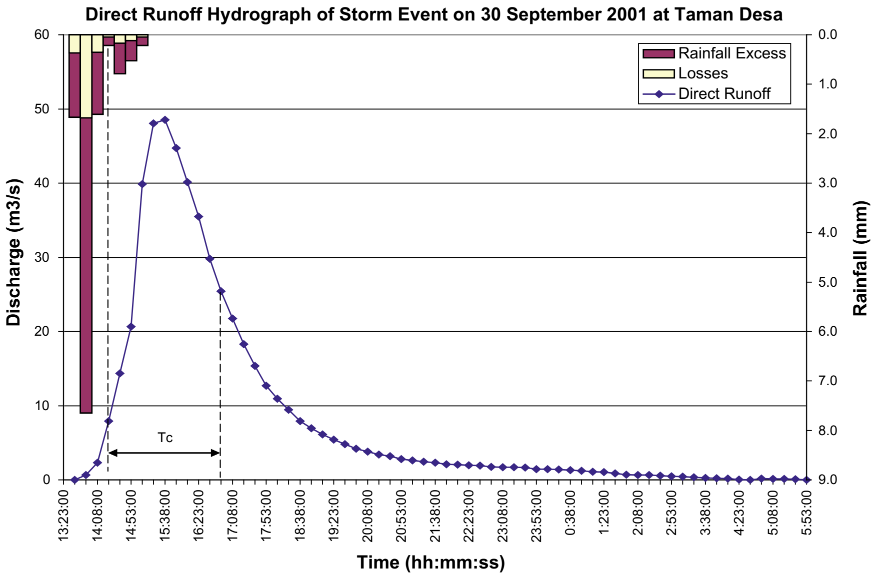

Fig. 4 T_c = 150 min (Taman Desa, 30-09-2001)

Table 4 Summary of estimated Tc for the study area by Baharudin [13] and newly included methods

Empirical equation name	T_c estimated for Taman Desa, min	T_c estimated for Taman Miharja, min	T_c estimated for Kg. Cheras Baru, min
Yen and Chow	176.1	117.8	42.2
NAASRA	141.8	83.5	32.2
Kerby	150.5	92.2	34.4
Bransby-Williams	348.8	196.5	103
Gundlach	80.07	76.65	82.91
Hakatnir-Sezen	217.36	117.79	64.80
Johnstone-Cross	178.60	116.99	85.91
Revised CUHP	47.664	73.05	73.04
Carter	136.5	85.11	57.14
Papadakis-Kazan	64.67	43.32	17.12
Ventura	548.16	420.44	443.44
Arizona DOT	192.77	150.60	113.07

The results for estimated T_c by Baharudin [13] and eight new methods are summarized in Table 4.

4 Results and Discussions

Nash–Sutcliffe efficiency index (NS) method was used to evaluate the reliability of results from the DRH plots and the empirical formulas. This was done between the estimated T_c and the observed T_c. The results for the newly estimated Tc and previous study results are summarized in Table 5 for the three catchments in the study area.

The results of the NS values varied for all the three catchment areas. The methods which presented the best values for the three sub-catchment areas were highlighted in red in Table 5. Among the eleven empirical formulas used to evaluate T_c for Kg. Cheras Baru, Carter equation showed the best agreement with the T_c value of 57.14 min when compared to average observed T_c of 52.5 min while the Ventura method performed worst. The Gundlach equation performed best in Taman Miharja catchment area with T_c value 76.65 min compared to the average observed T_c of 79.5 min and Ventura still maintained worst performance for the catchment. The NAASRA equation maintained its best position of evaluating T_c for Kg. Cheras Baru from previous study of the catchment area and the Ventura and Bransby-Williams equation performed worst for this catchment as well. The reason for this poor output is because both methods have been recommended for estimation of time of concentration rural basins from previous studies.

Table 5 NS values obtained for the Tc empirical equation in comparison to observed Tc

Empirical equation	Catchment area		
	Kg. Cheras Baru	Taman Miharja	Taman Desa
Revised CUHP	−1.6521	−0.1311	−11.3244
Gundlach	−3.6116	**−0.0256**	−4.7424
Hakatnir-Sezen	−0.6006	−4.6214	−8.1399
Johnstone-Cross	−4.3576	−4.4303	−2.0528
Carter	**−0.0921**	−0.0992	−0.0121
Papadakis-Kazan	−4.8856	−4.1261	−7.5187
Ventura	−595.5261	−366.3990	−224.2403
Arizona DOT	−14.3034	−15.9345	−3.8103
Yen and Chow	−0.4216	−4.6238	−1.7987
NAASRA	−1.6139	−0.0504	**−0.0071**
Kerby	−1.2848	−0.5084	−0.1625
Bransby-Williams	−9.9453	−43.1489	−58.8204

5 Conclusion

Identifying the sensitivity of time of concentration is very crucial in evaluating the response time of runoff generation in an urban catchment. In this review study, Gundlach, Hakatnir-Sezen, Carter, Johnstone-Cross, revised CUHP, Papadakis-Kazan, Ventura and Arizona DOT empirical methods were used to further estimate the value of time of concentration of Sungai Kerayong urban catchment area of Kuala Lumpur, Malaysia. Previous study used rainfall-runoff hydrograph analysis and four empirical methods in estimation of T_c. From the findings of the study Gundlach, Carter and NAASRA methods performed best in estimating T_c and can be adopted in the region. Gundlach, NAASRA and Carter methods level of performance can be attributed to the method incorporating impervious fraction, area, length, roughness coefficient and slope which are important parameters in an urban catchment while the Bransby-Williams and Ventura can be concluded not suitable for evaluating T_c for an urban catchment. It can be recommended from this study findings that further data of time of concentration from several catchments by different methods can be gathered for machine learning like SVM, ANN which can help in predicting time of concentration of various catchment characteristics.

Appendix

See Figs. 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60 and 61.

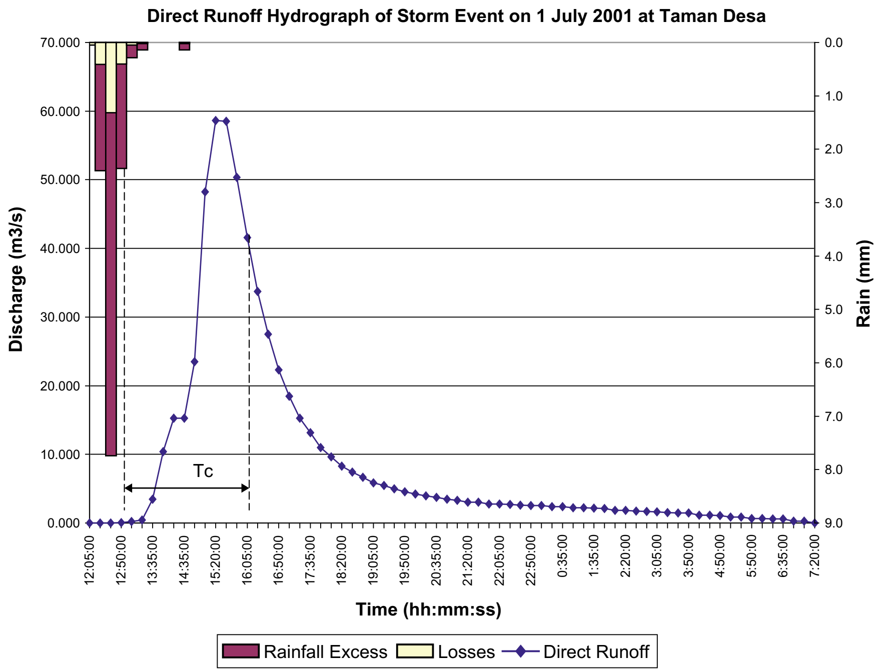

Fig. 5 T_c = 195 min (Taman Desa, 01-07-2001)

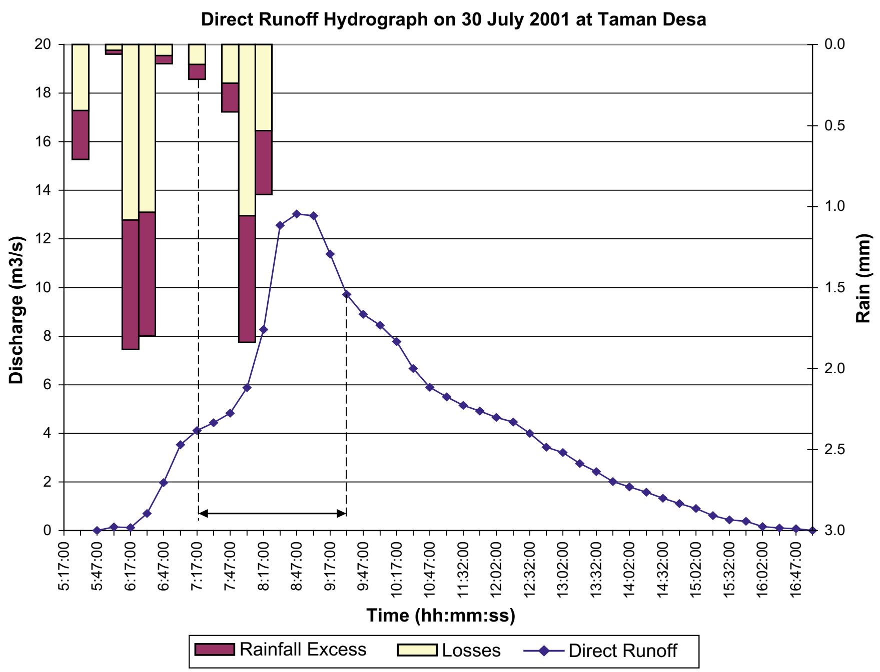

Fig. 6 T_c = 135 min (Taman Desa, 30-07-2001)

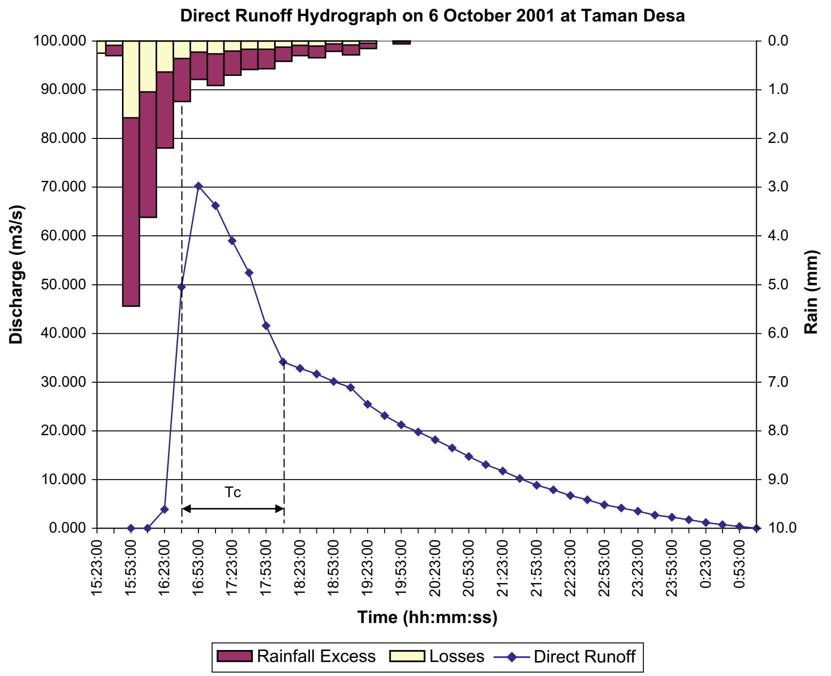

Fig. 7 T_c = 135 min (Taman Desa, 06-10-2001)

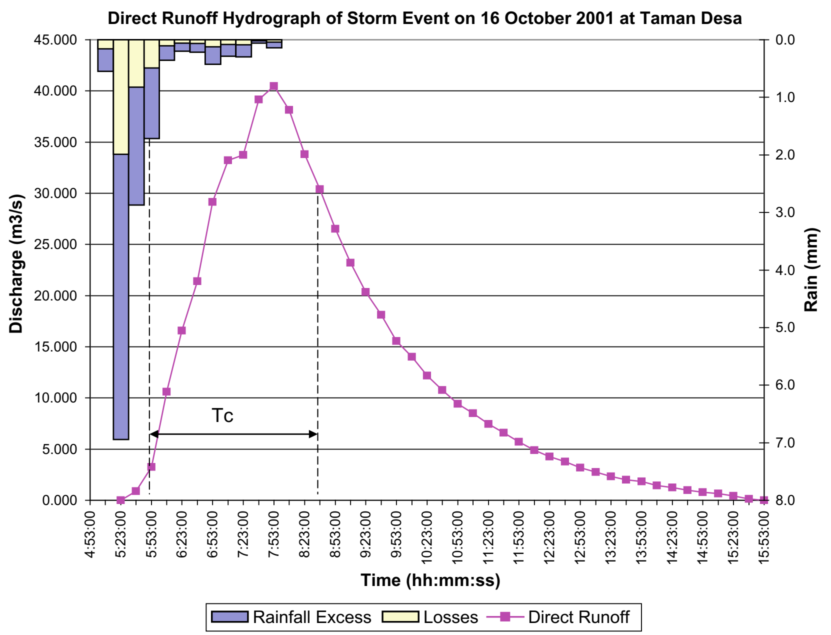

Fig. 8 T_c = 165 min (Taman Desa, 16-10-2001)

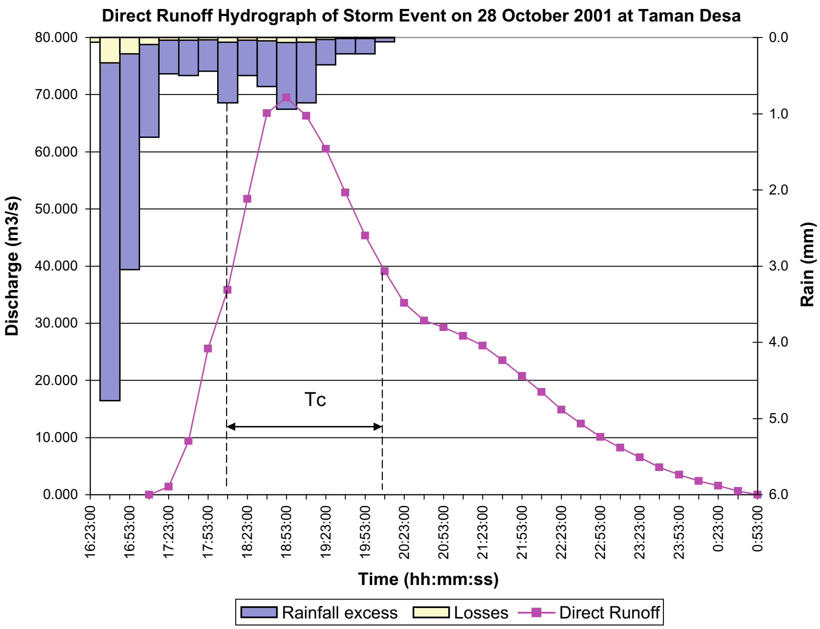

Fig. 9 T_c = 120 min (Taman Desa, 28-10-2001)

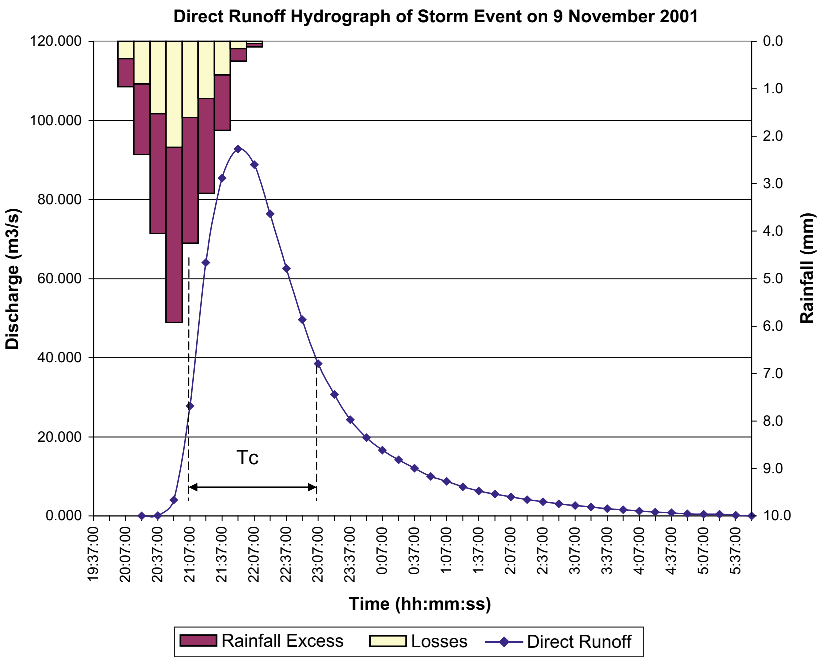

Fig. 10 T_c = 120 min (Taman Desa, 09-11-2001)

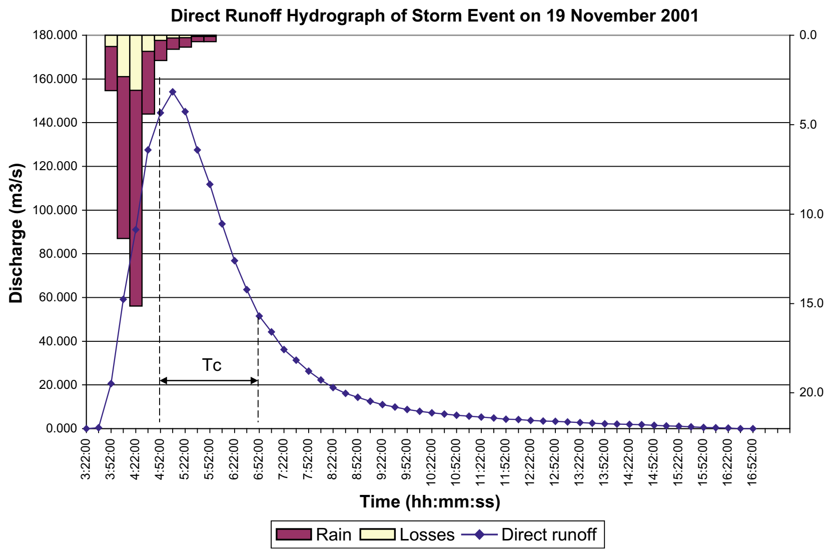

Fig. 11 T_c = 120 min (Taman Desa, 19-11-2001)

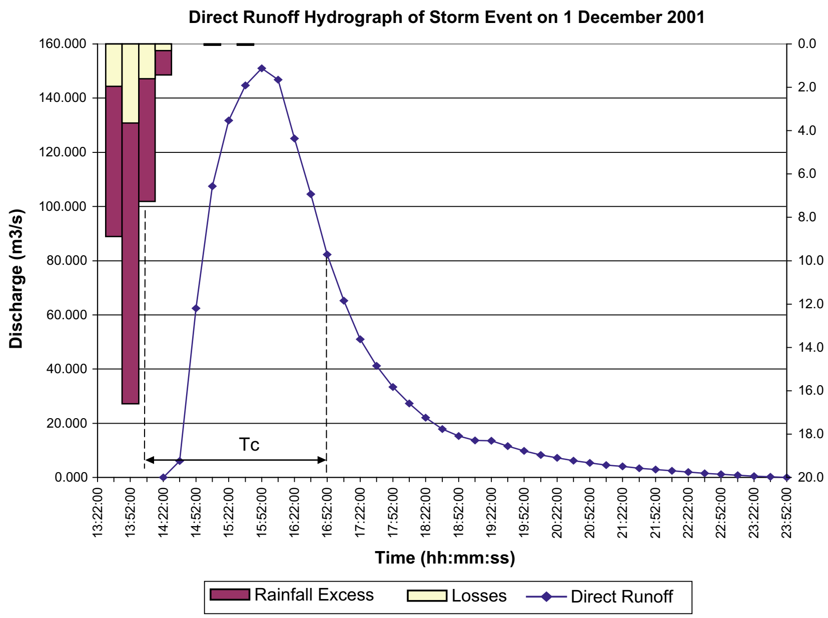

Fig. 12 T_c = 165 min (Taman Desa, 01-12-2002)

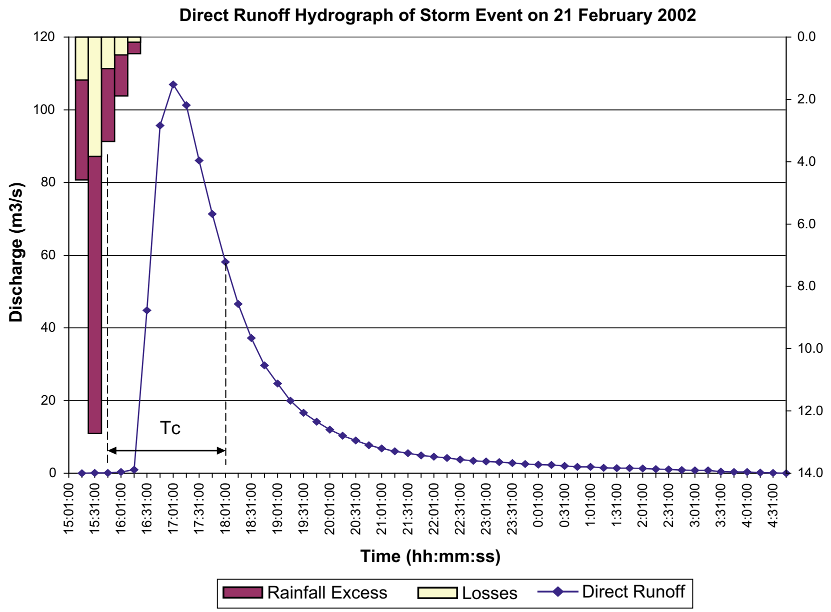

Fig. 13 T_c = 135 min (Taman Desa, 21-02-2002)

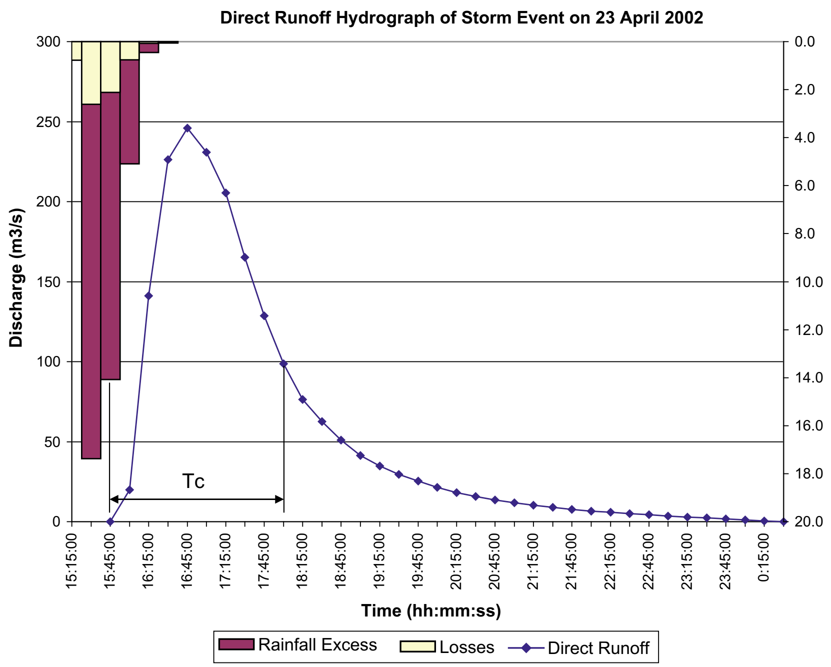

Fig. 14 T_c = 135 min (Taman Desa, 23-04-2002)

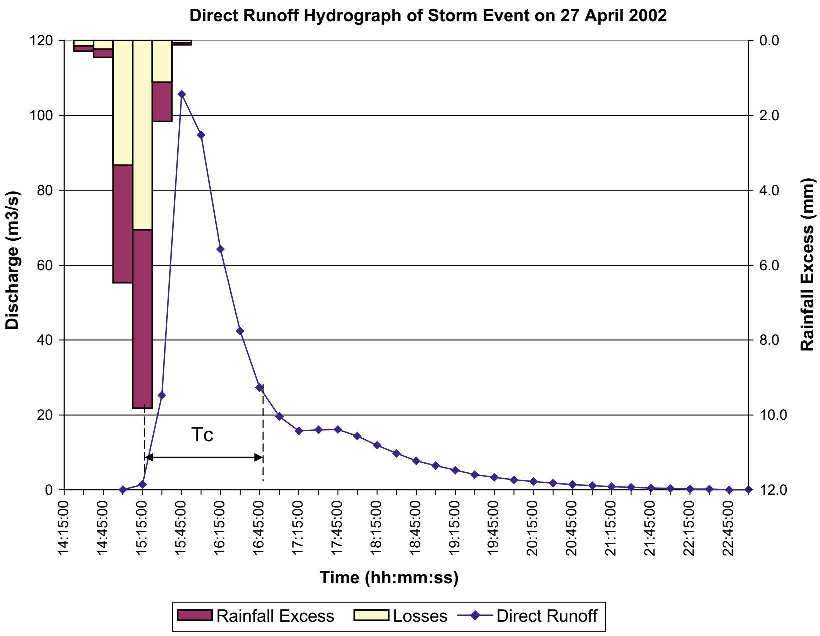

Fig. 15 T_c = 90 min (Taman Desa, 27-04-2002)

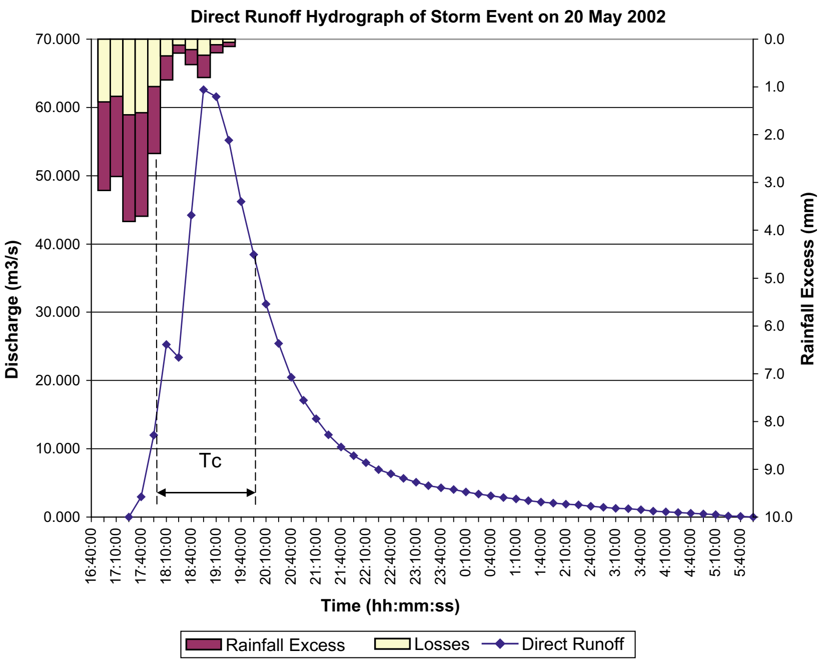

Fig. 16 T_c = 120 min (Taman Desa, 20-05-2002)

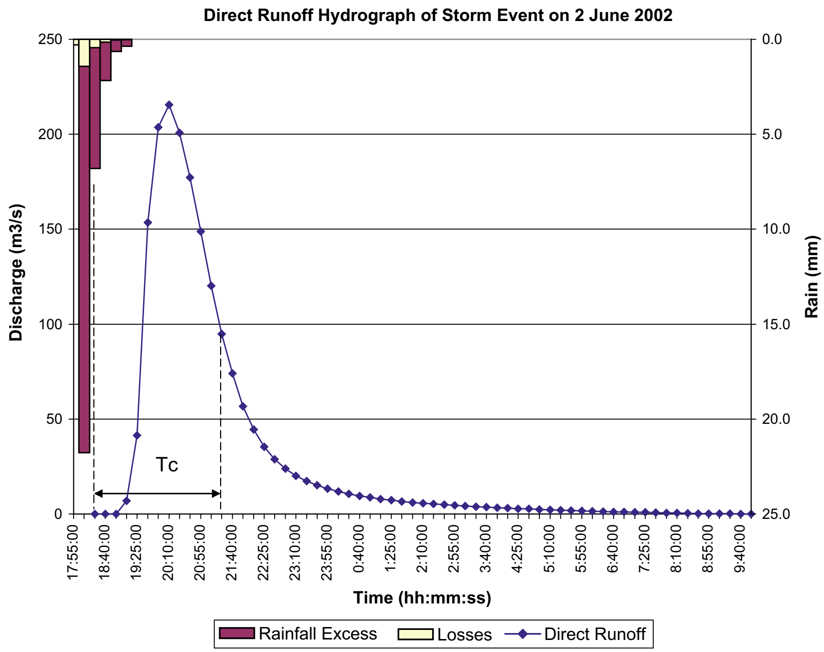

Fig. 17 T_c = 180 min (Taman Desa, 02-06-2002)

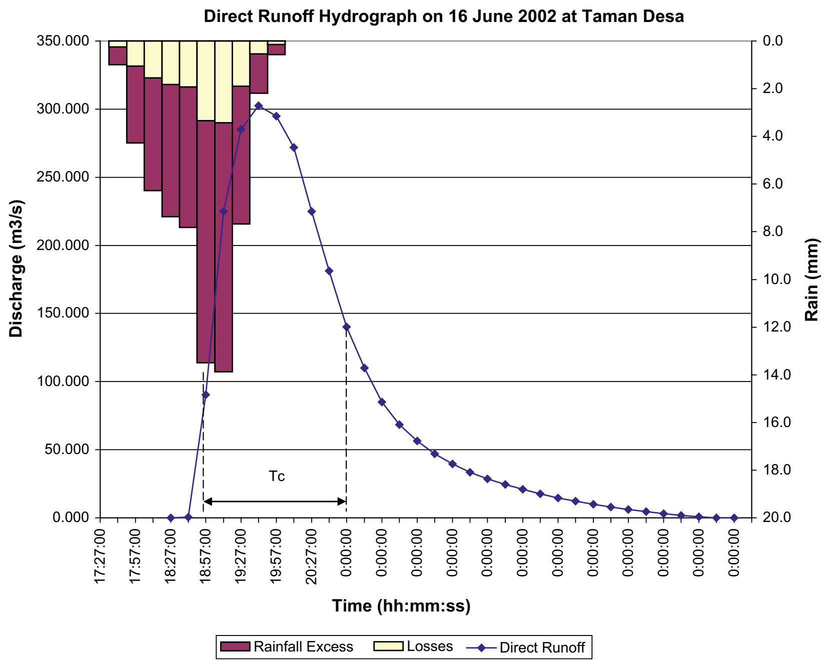

Fig. 18 T_c = 120 min (Taman Desa, 16-06-2002)

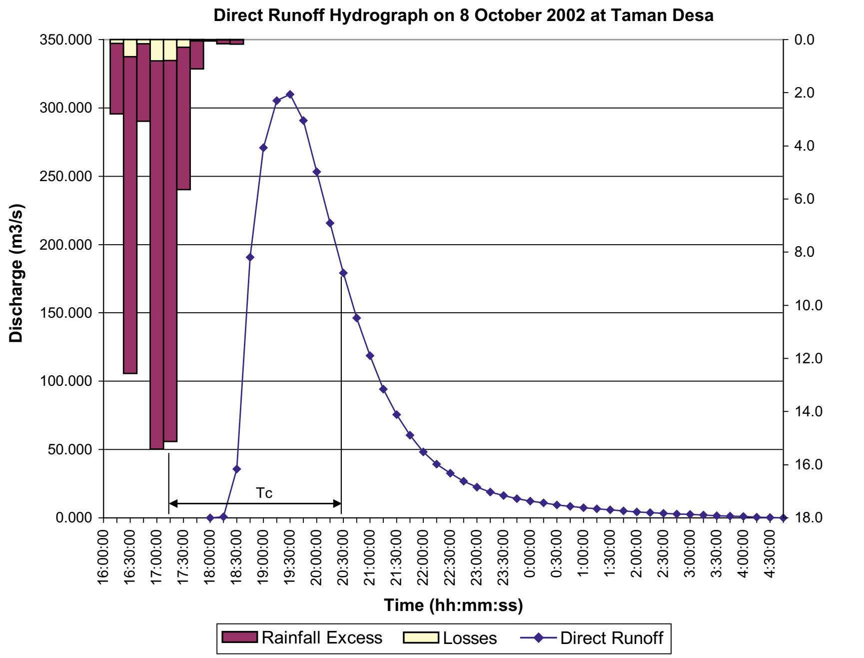

Fig. 19 T_c = 195 min (Taman Desa, 08-10-2002)

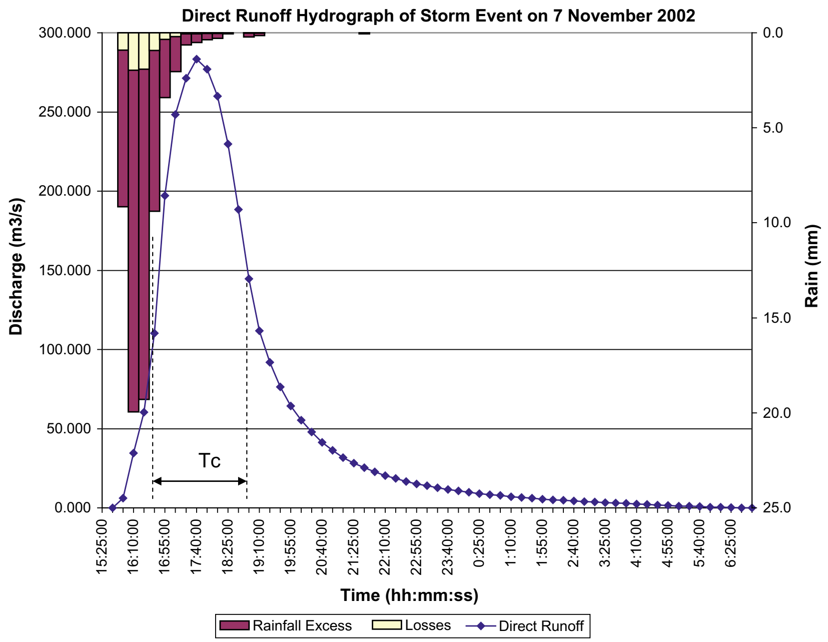

Fig. 20 T_c = 135 min (Taman Desa, 07-10-2002)

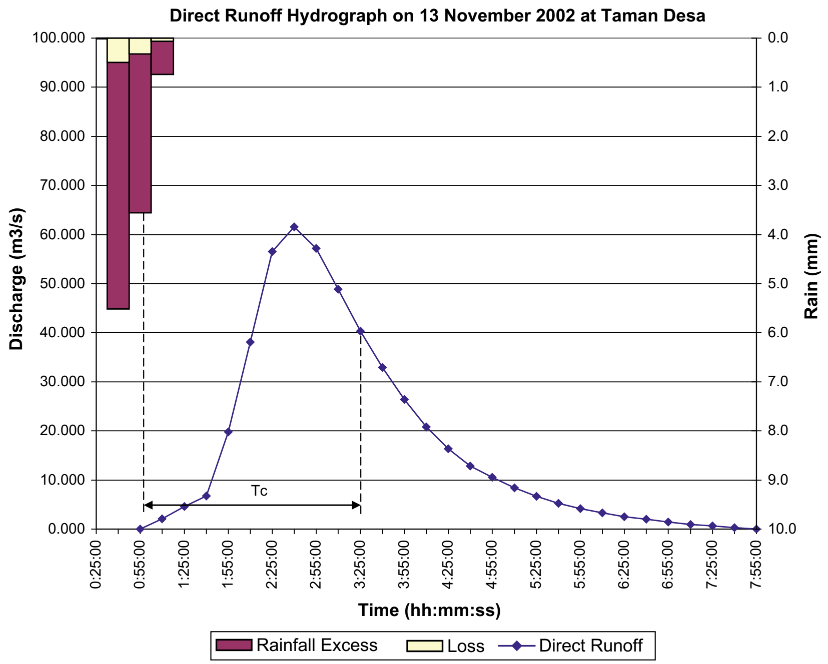

Fig. 21 T_c = 150 min (Taman Desa, 13-11-2002)

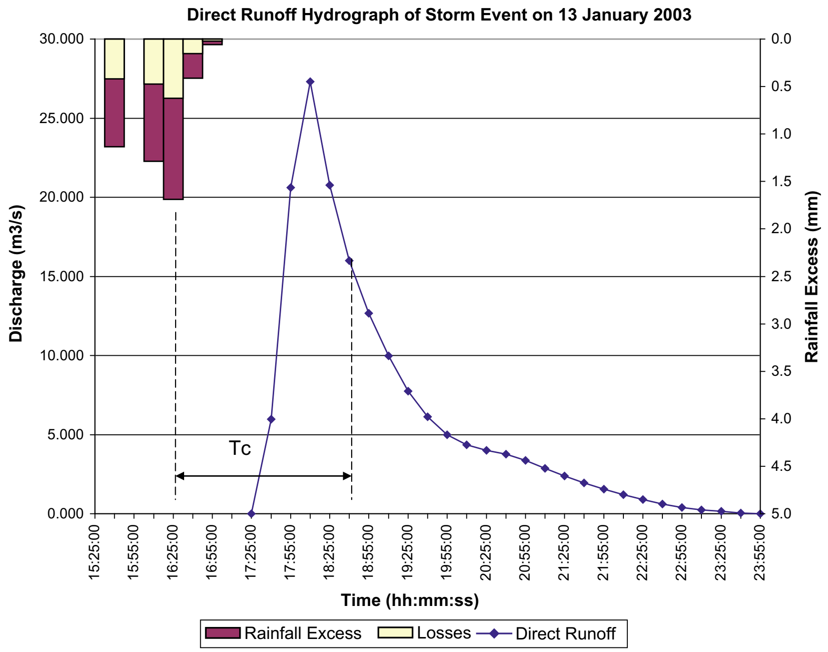

Fig. 22 T_c = 135 min (Taman Desa, 13-01-2003)

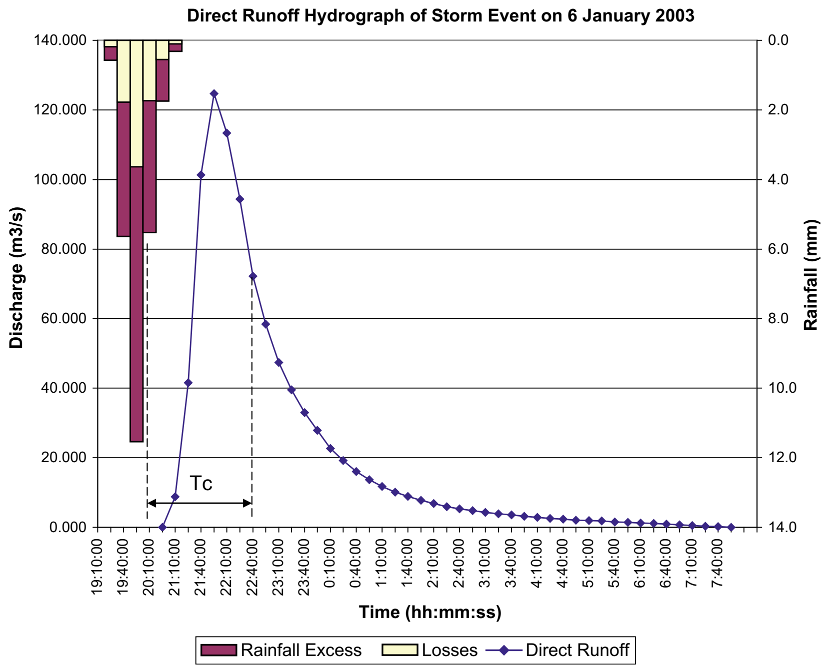

Fig. 23 T_c = 150 min (Taman Desa, 06-01-2003)

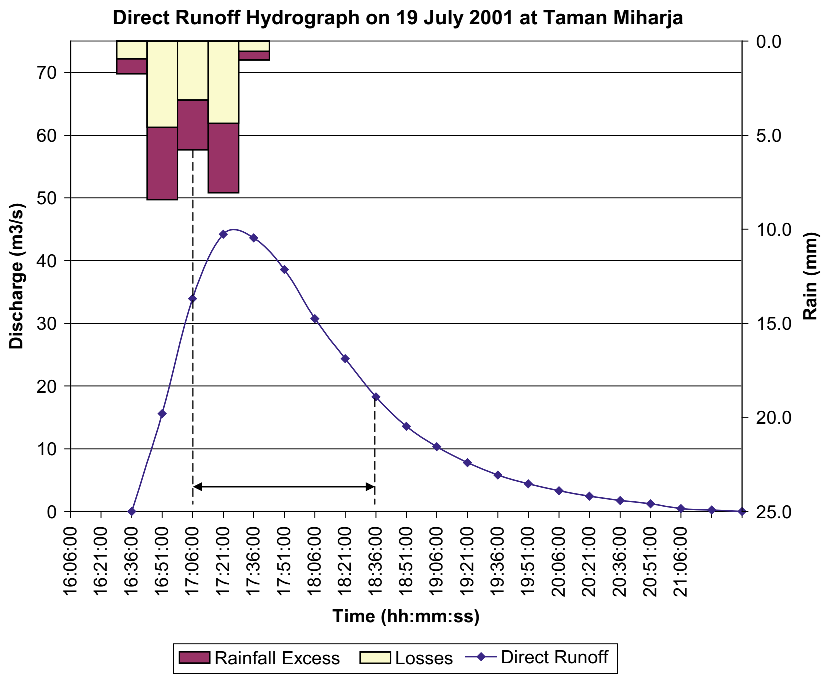

Fig. 24 T_c = 90 min (Taman Miharja, 19-07-2001)

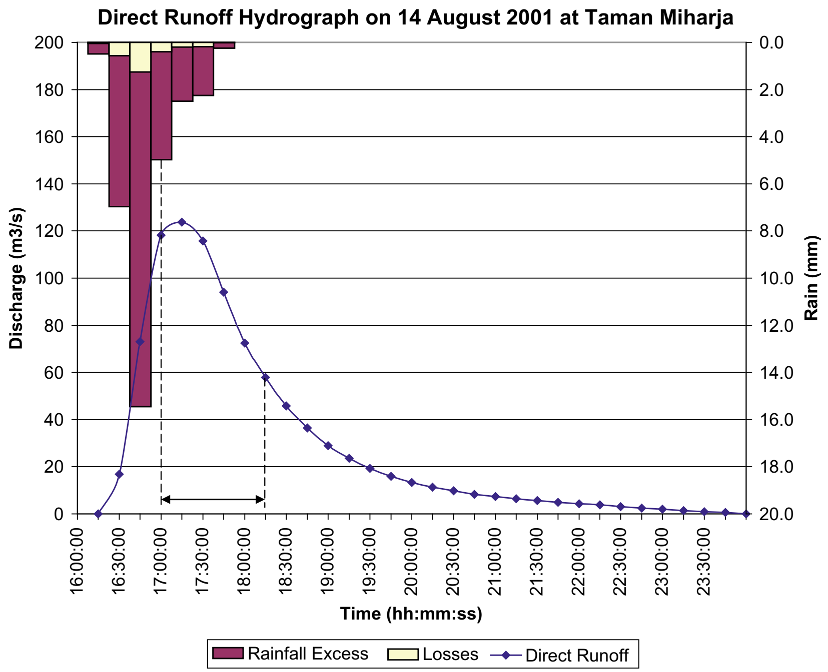

Fig. 25 T_c = 75 min (Taman Miharja, 14-08-2001)

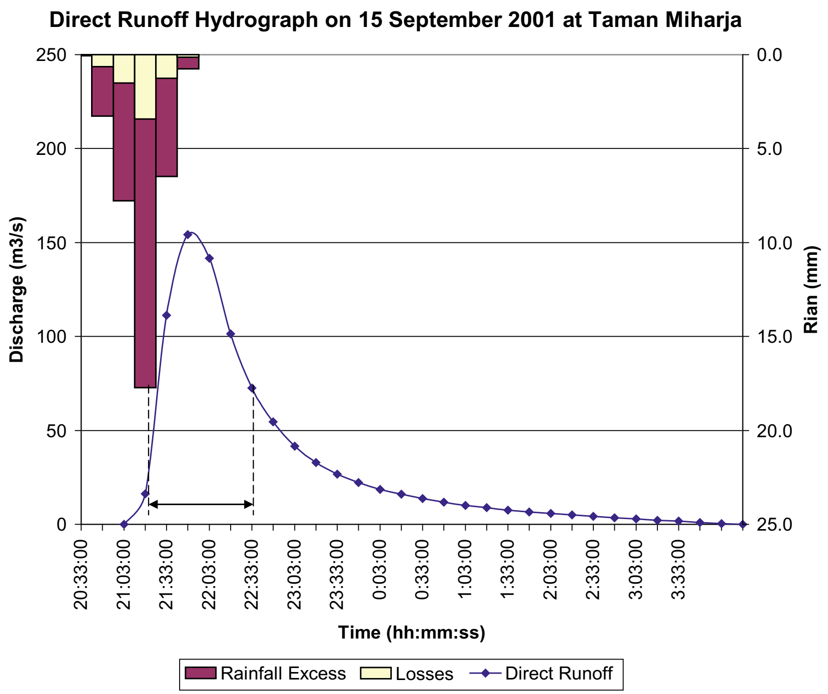

Fig. 26 T_c = 75 min (Taman Miharja, 15-09-2001)

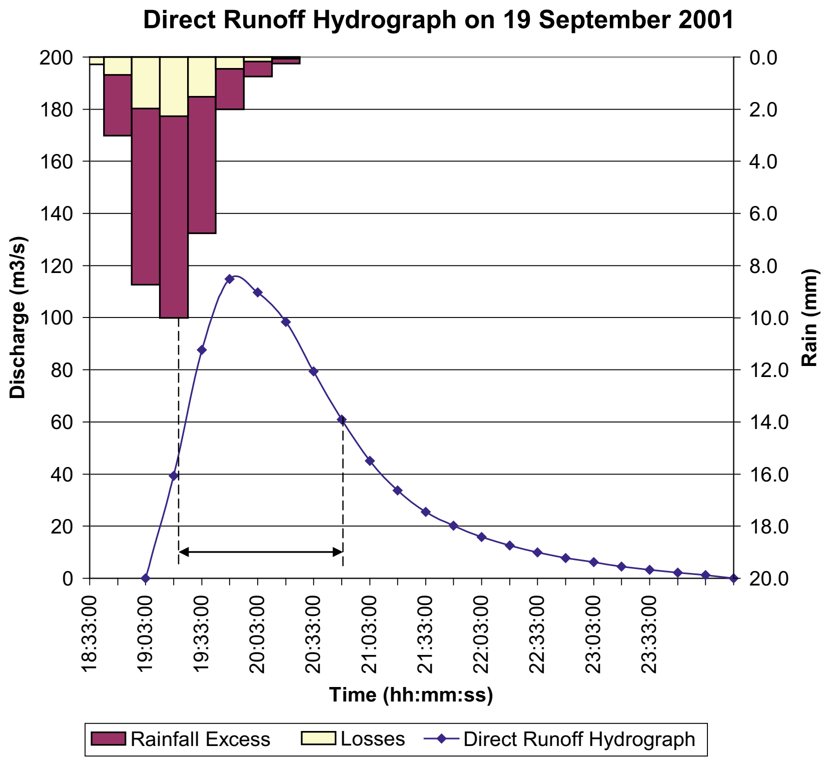

Fig. 27 T_c = 90 min (Taman Miharja, 19-09-2001)

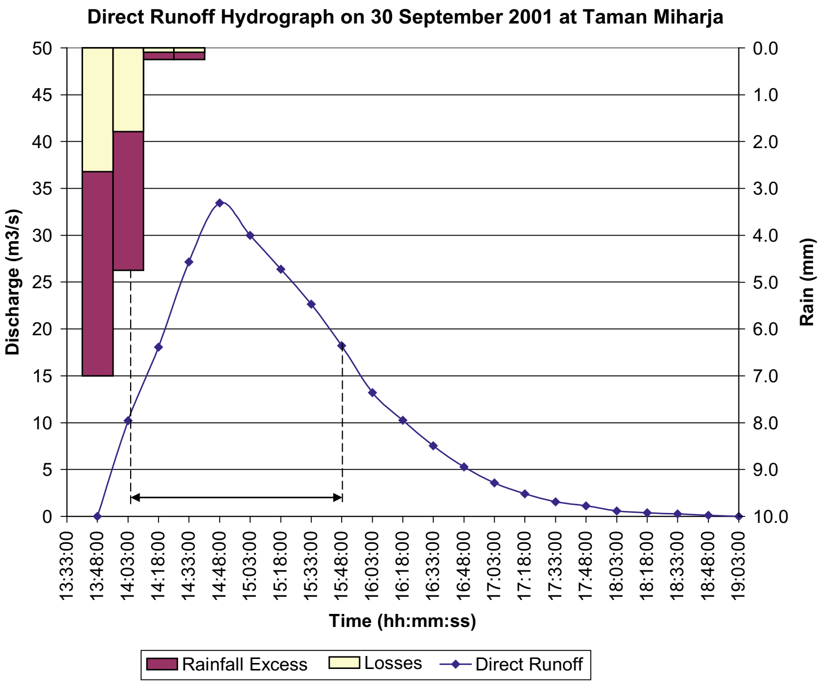

Fig. 28 T_c = 105 min (Taman Miharja, 30-09-2001)

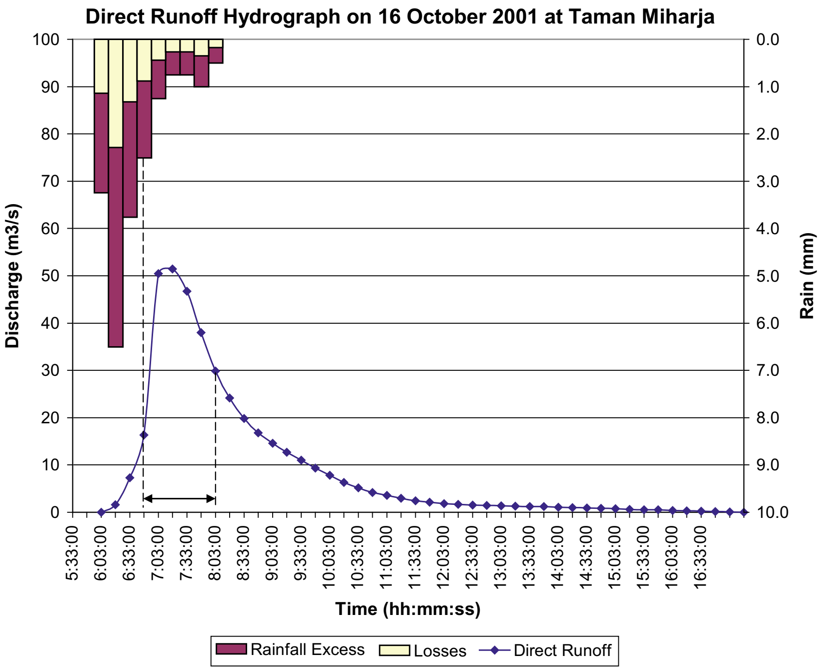

Fig. 29 T_c = 75 min (Taman Miharja, 16-10-2001)

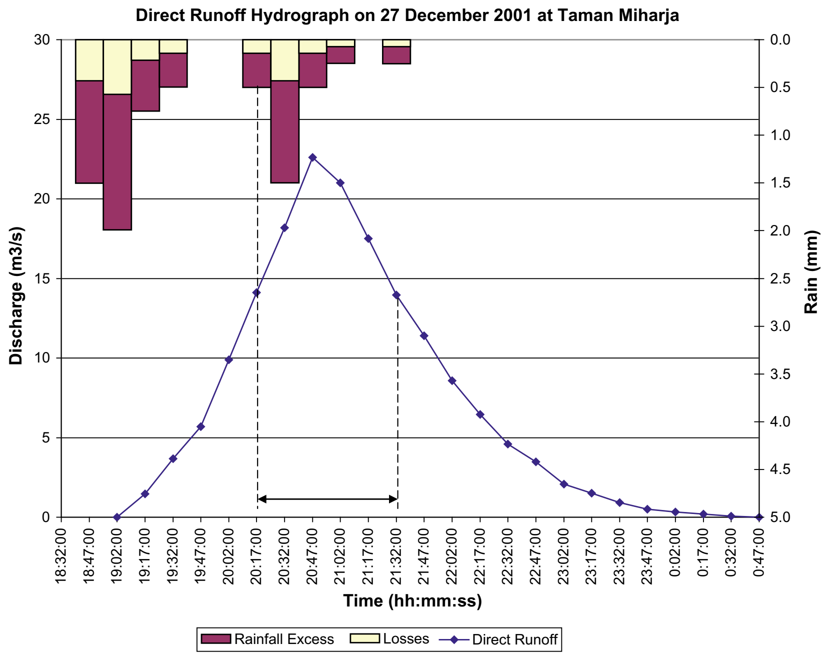

Fig. 30 T_c = 75 min (Taman Miharja, 27-12-2001)

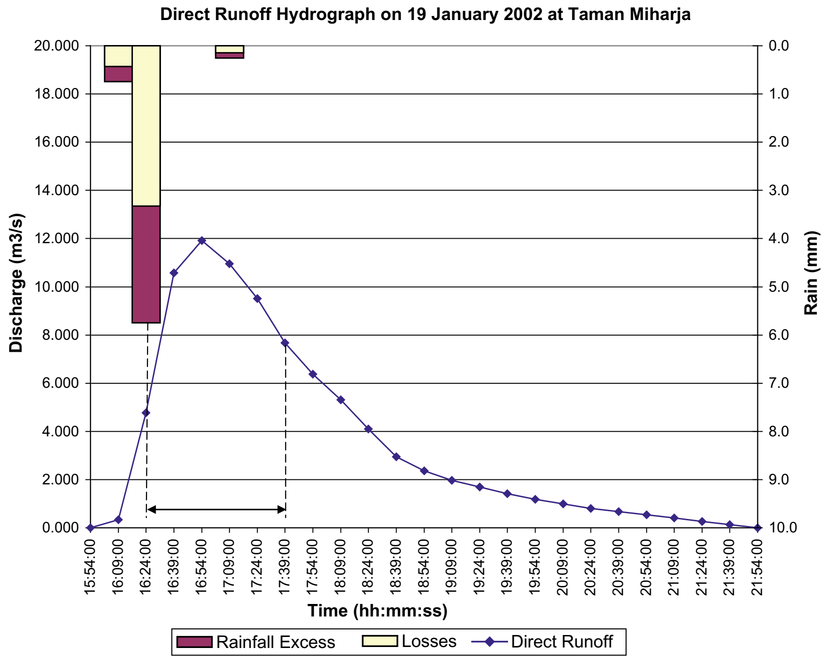

Fig. 31 T_c = 75 min (Taman Miharja, 19-01-2002)

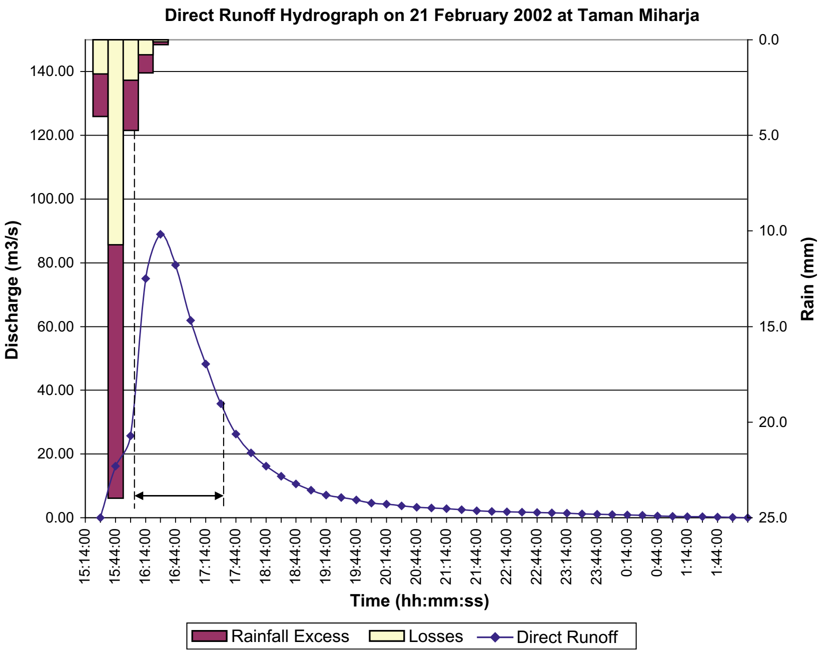

Fig. 32 T_c = 90 min (Taman Miharja, 21-02-2002)

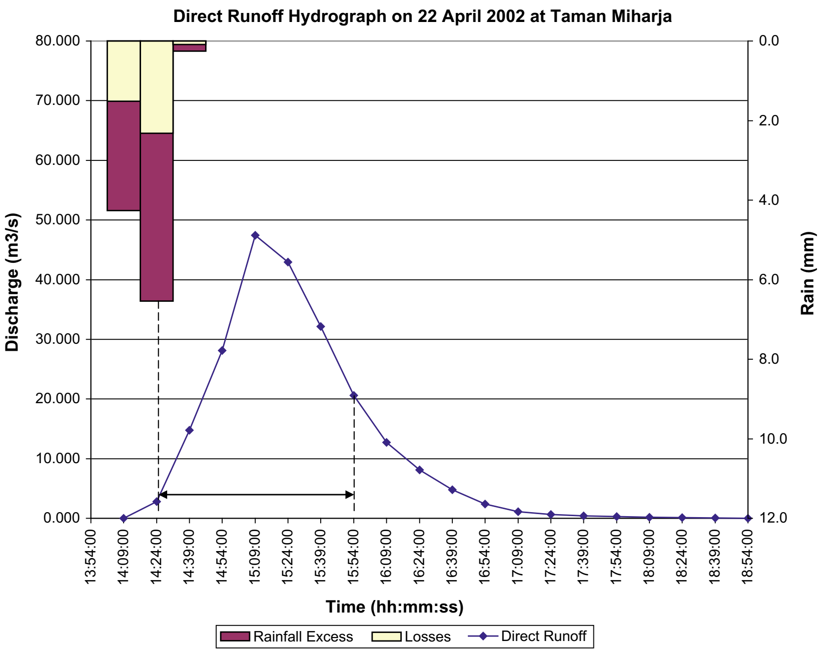

Fig. 33 T_c = 90 min (Taman Miharja, 22-04-2002)

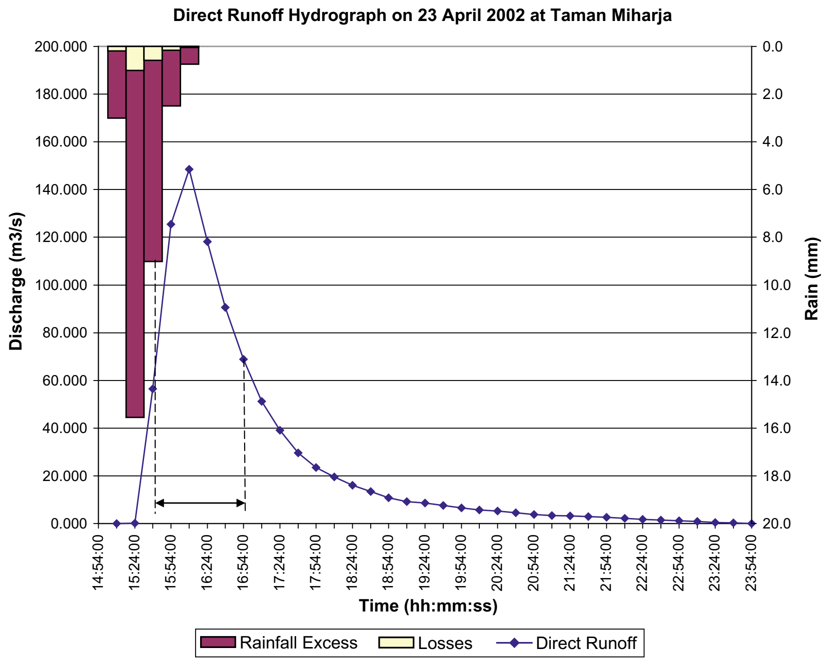

Fig. 34 T_c = 75 min (Taman Miharja, 23-04-2002)

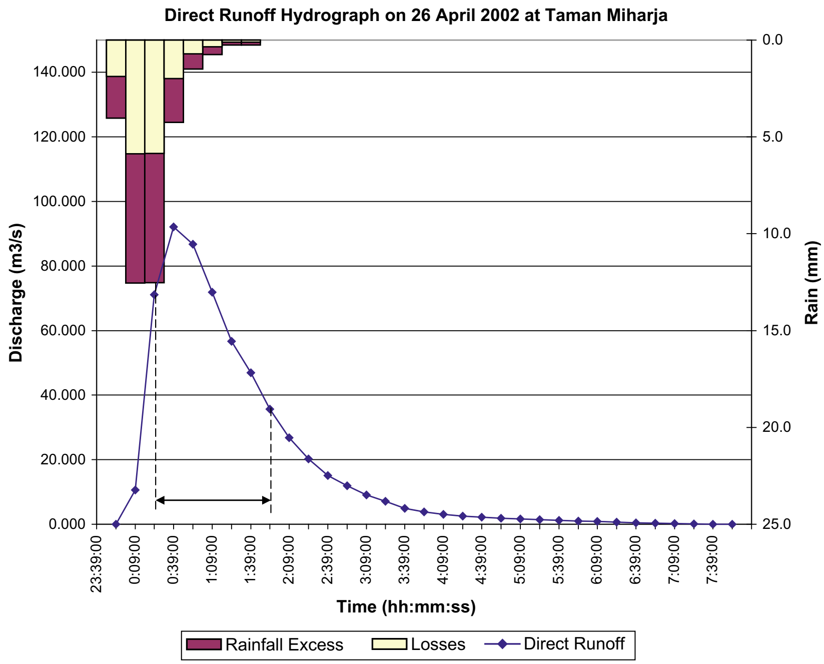

Fig. 35 T_c = 90 min (Taman Miharja, 26-04-2002)

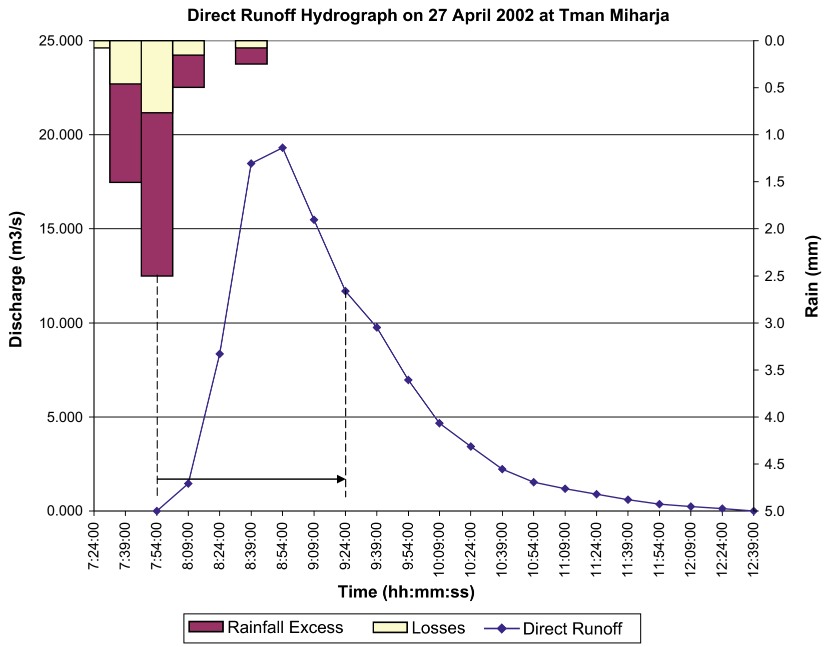

Fig. 36 T_c = 90 min (Taman Miharja, 27-04-2002)

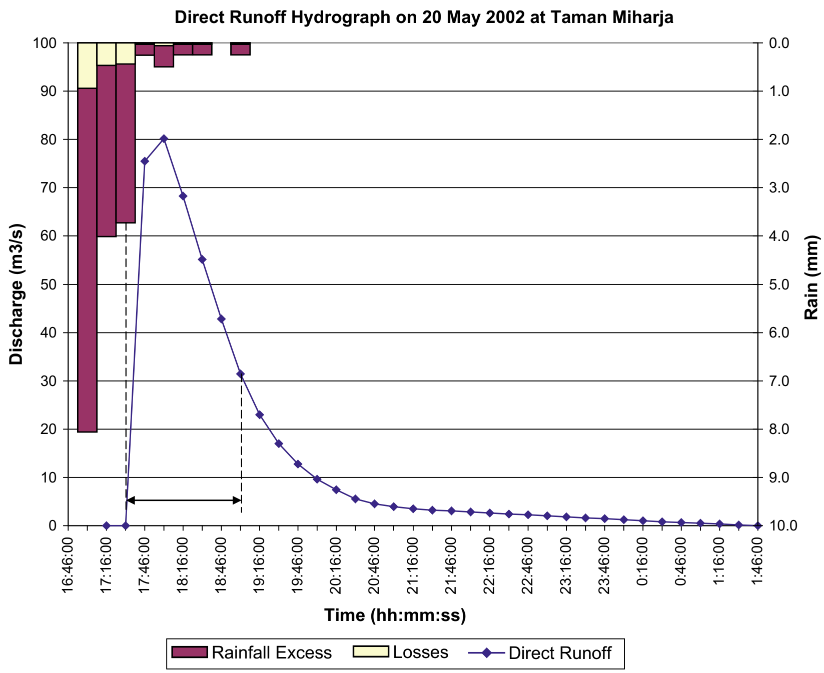

Fig. 37 T_c = 90 min (Taman Miharja, 20-05-2002)

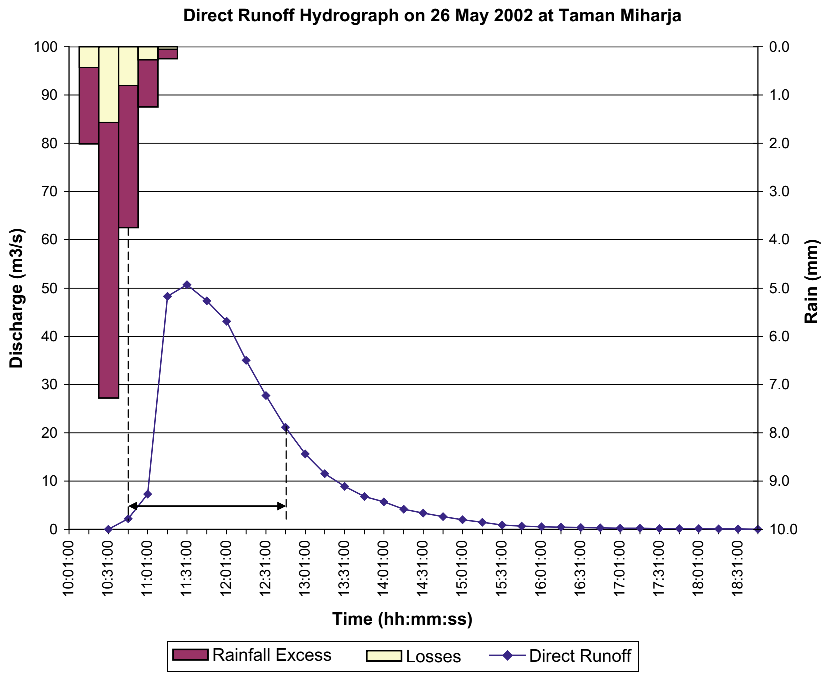

Fig. 38 T_c = 120 min (Taman Miharja, 26-05-2002)

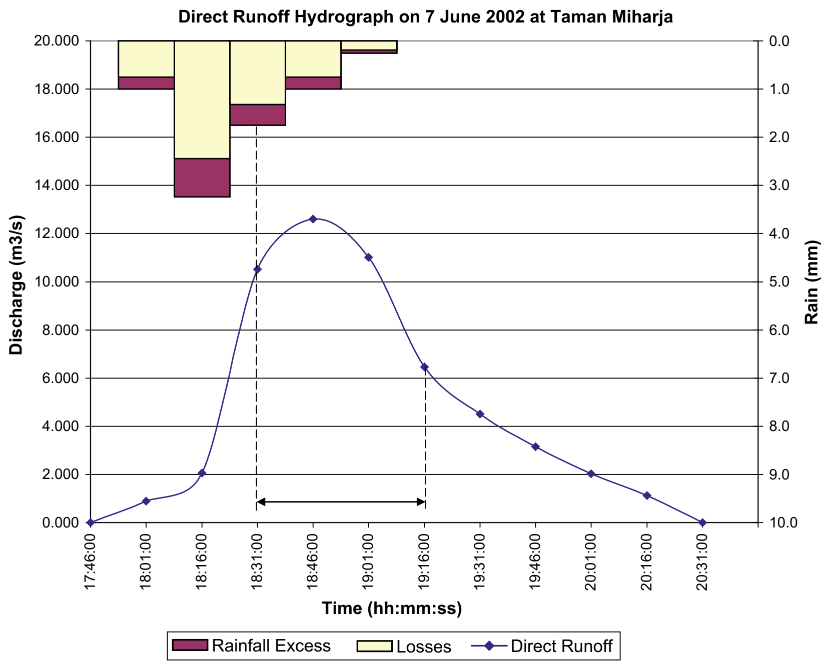

Fig. 39 T_c = 45 min (Taman Miharja, 07-06-2002)

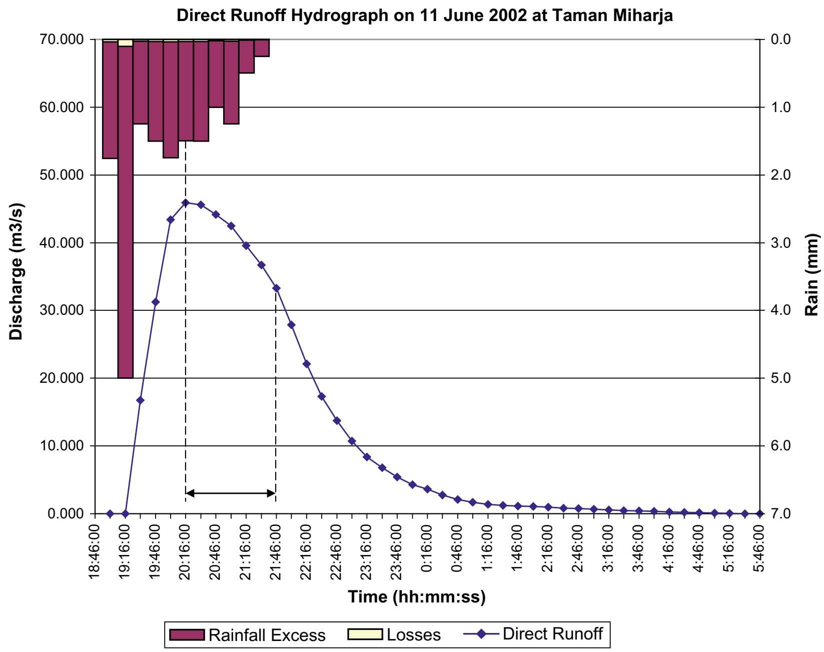

Fig. 40 T_c = 90 min (Taman Miharja, 11-06-2002)

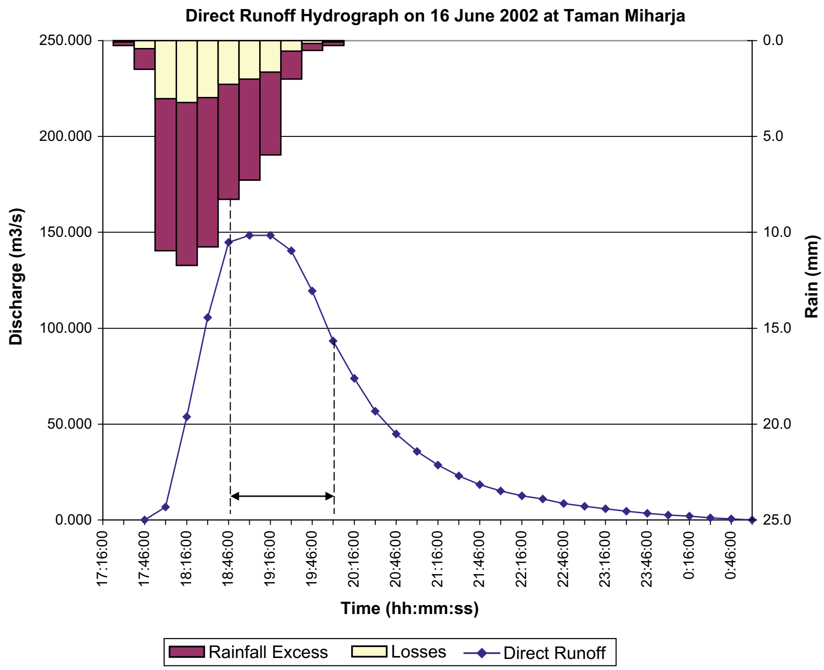

Fig. 41 T_c = 75 min (Taman Miharja, 16-06-2002)

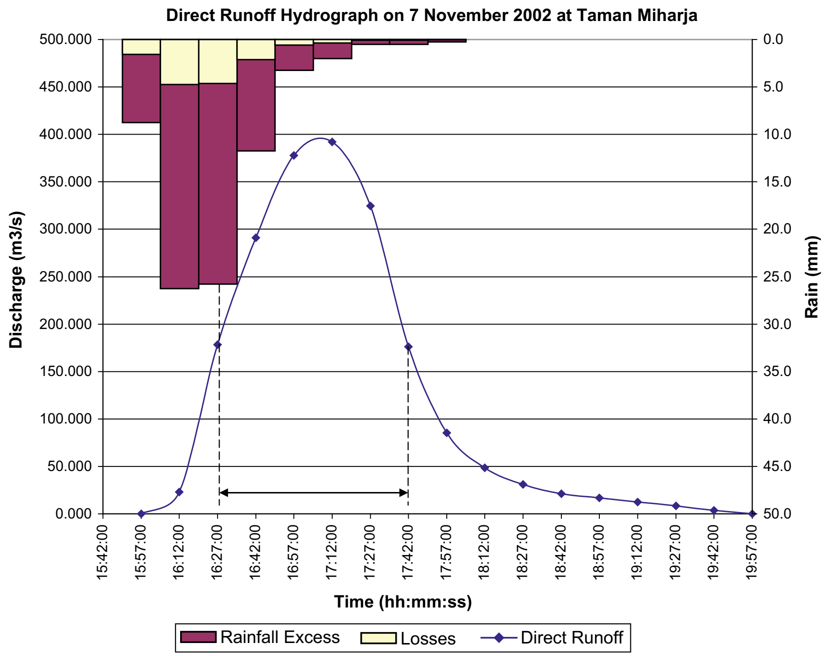

Fig. 42 T_c = 75 min (Taman Miharja, 07-11-2002)

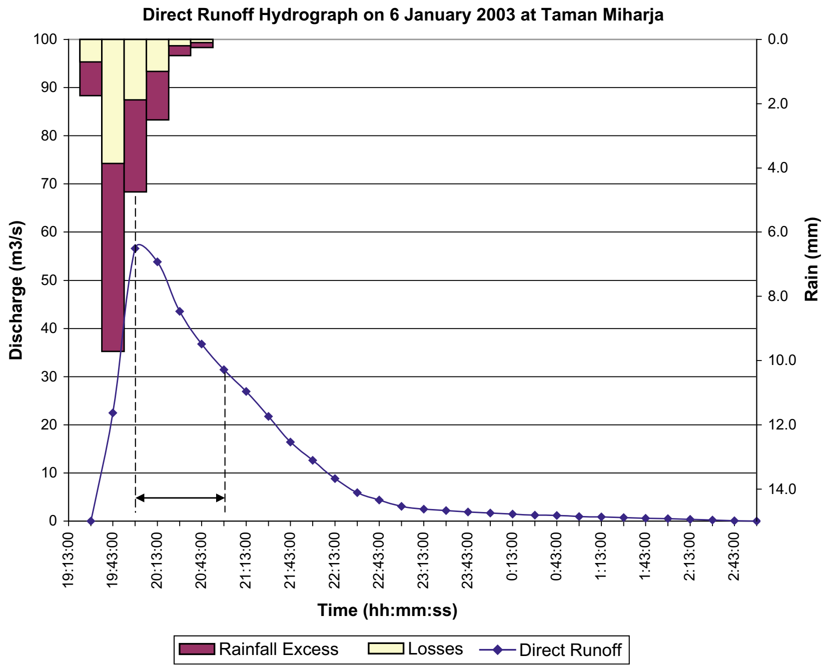

Fig. 43 T_c = 75 min (Taman Miharja, 06-01-2003)

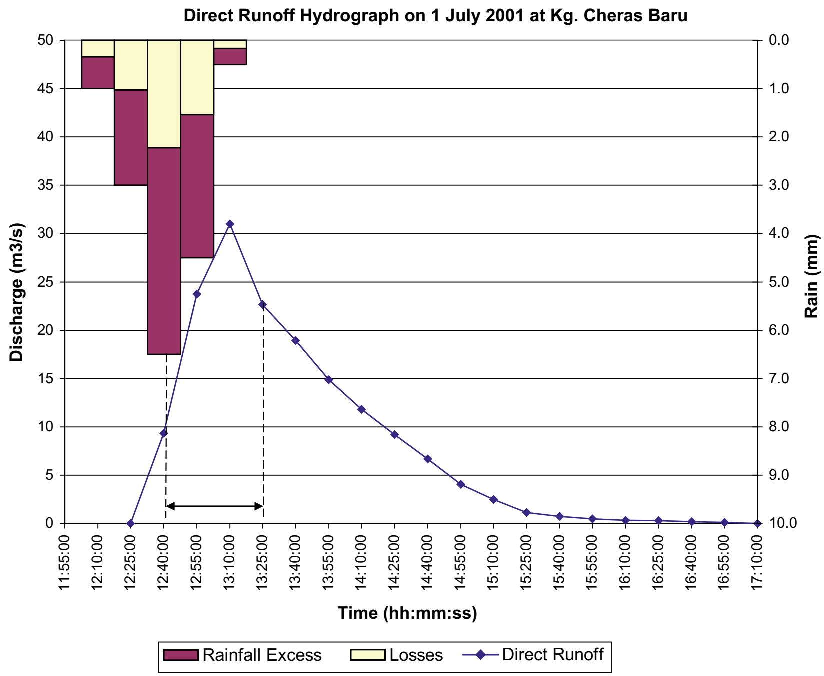

Fig. 44 T_c = 45 min (Kg. Cheras Baru, 01-07-2001)

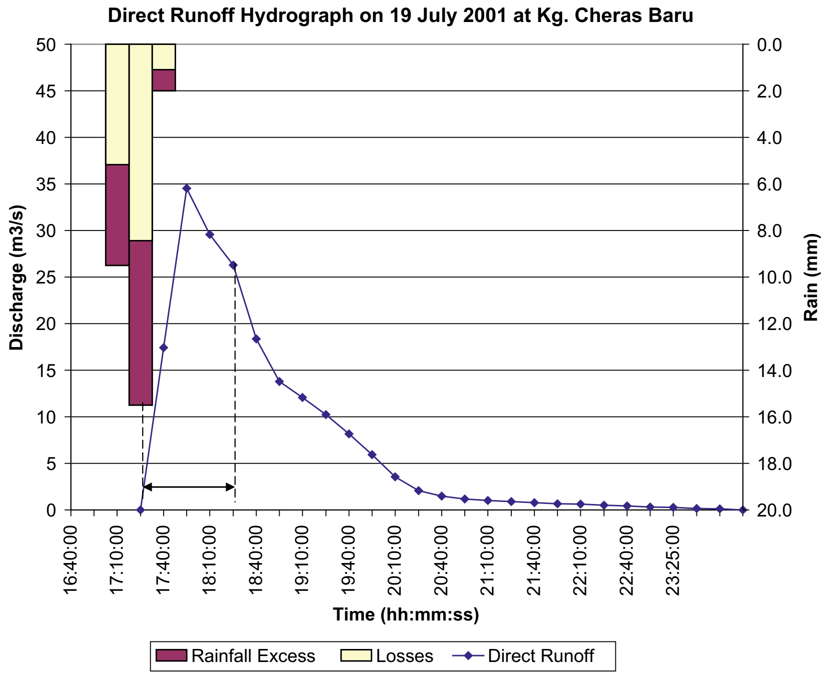

Fig. 45 T_c = 60 min (Kg. Cheras Baru, 09-07-2001)

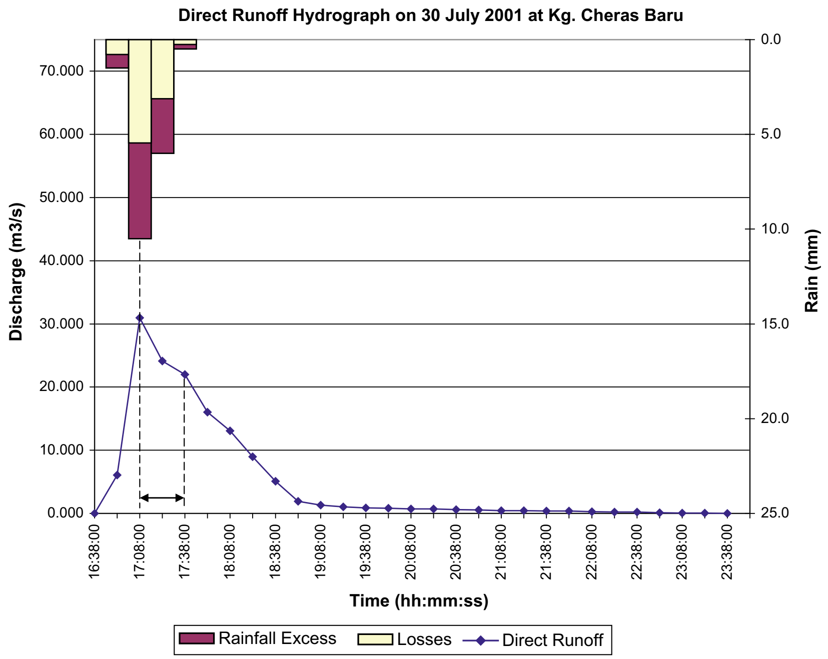

Fig. 46 T_c = 30 min (Kg. Cheras Baru, 30-07-2001)

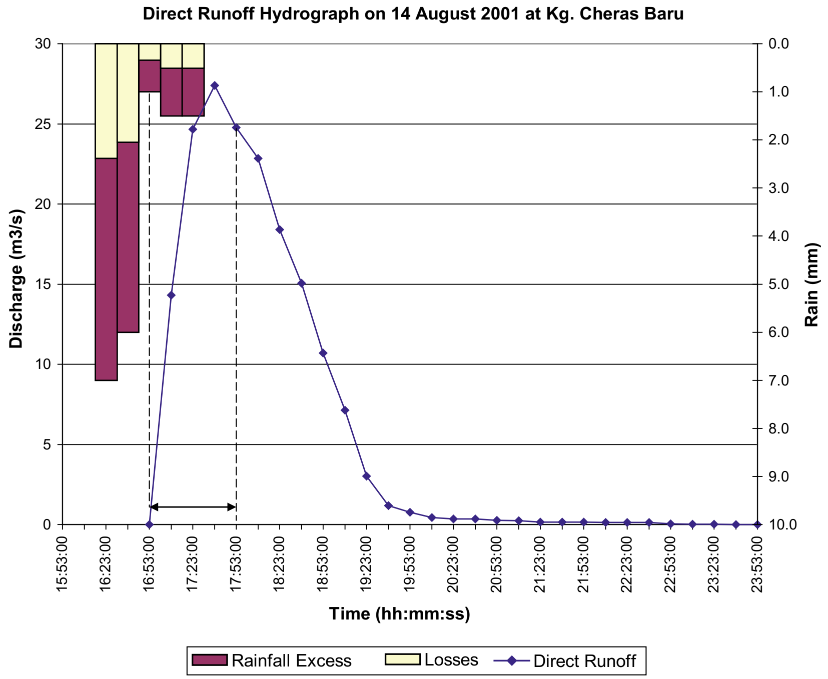

Fig. 47 T_c = 60 min (Kg. Cheras Baru, 14-08-2001)

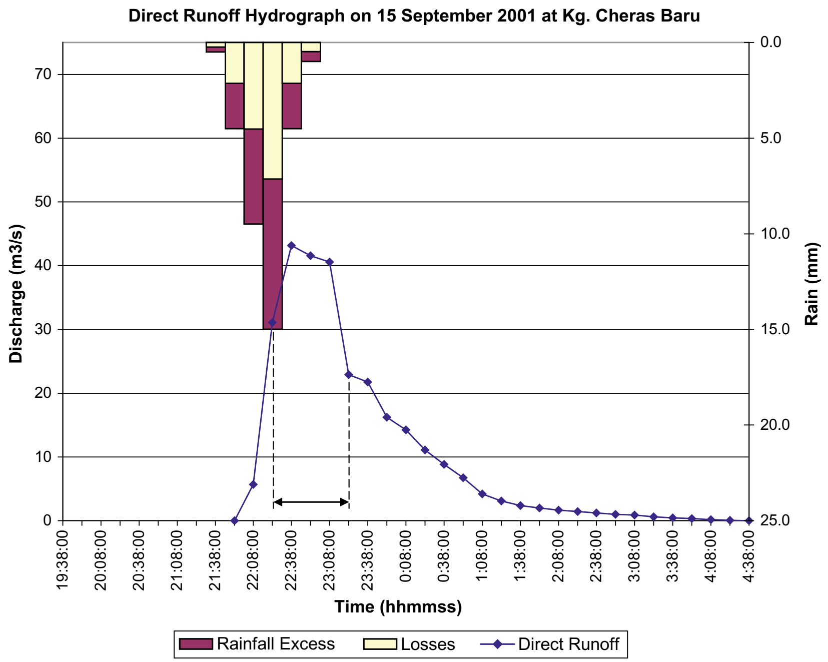

Fig. 48 T_c = 60 min (Kg. Cheras Baru, 15-09-2001)

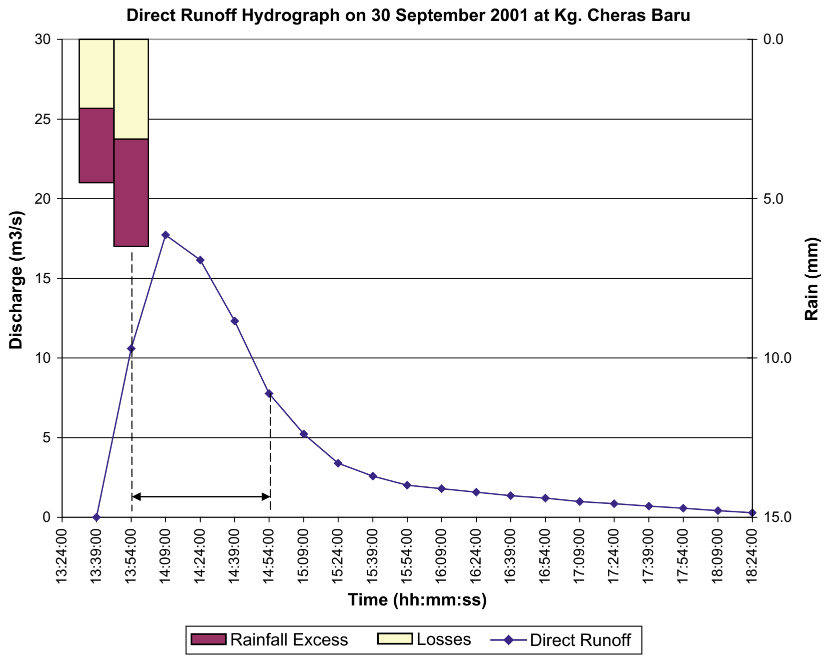

Fig. 49 T_c = 60 min (Kg. Cheras Baru, 30-09-2001)

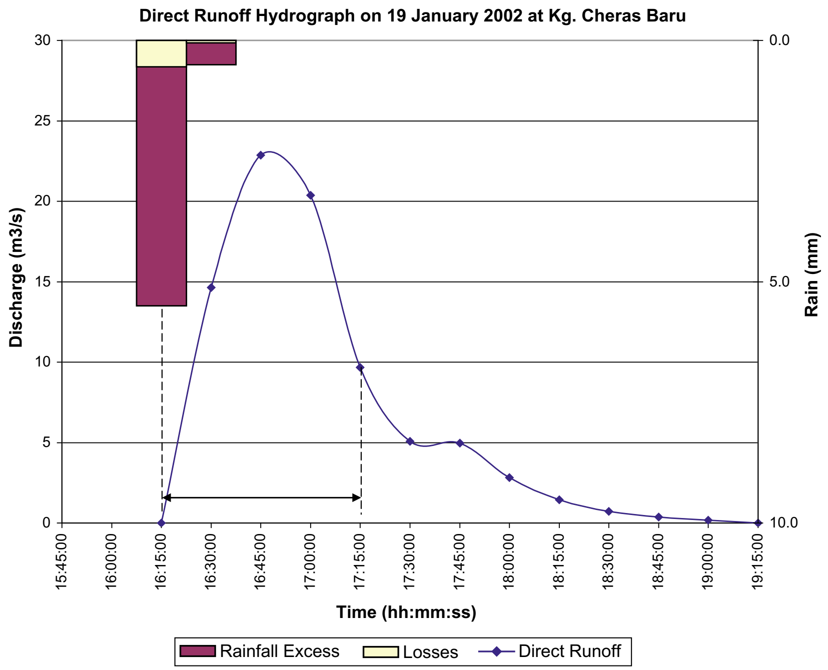

Fig. 50 T_c = 60 min (Kg. Cheras Baru, 19-01-2002)

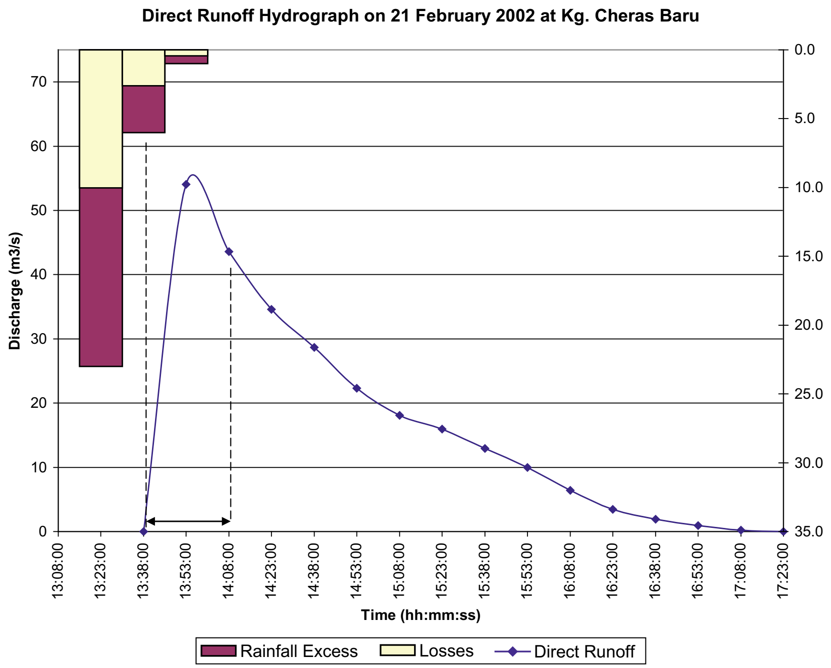

Fig. 51 T_c = 30 min (Kg. Cheras Baru, 21-02-2002)

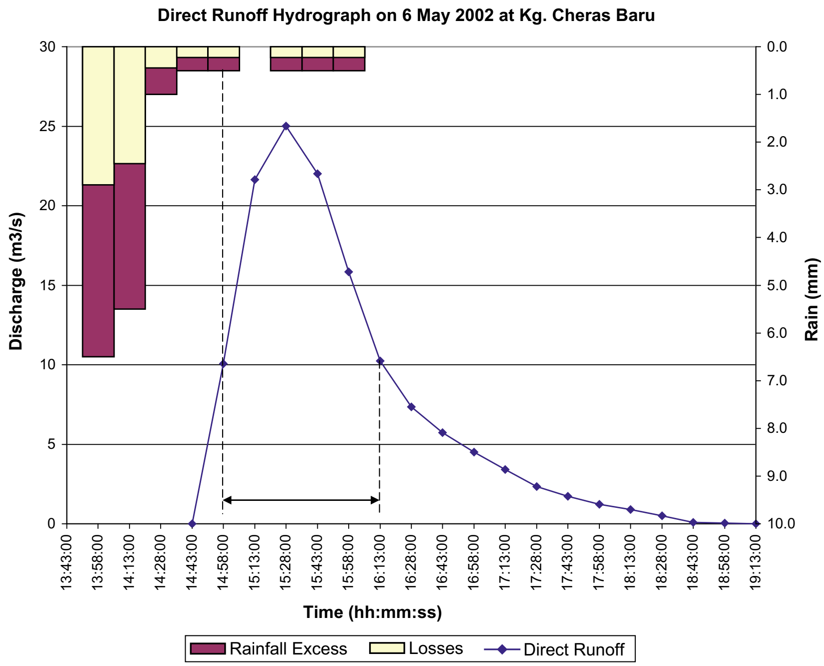

Fig. 52 T_c = 75 min (Kg. Cheras Baru, 06-05-2002)

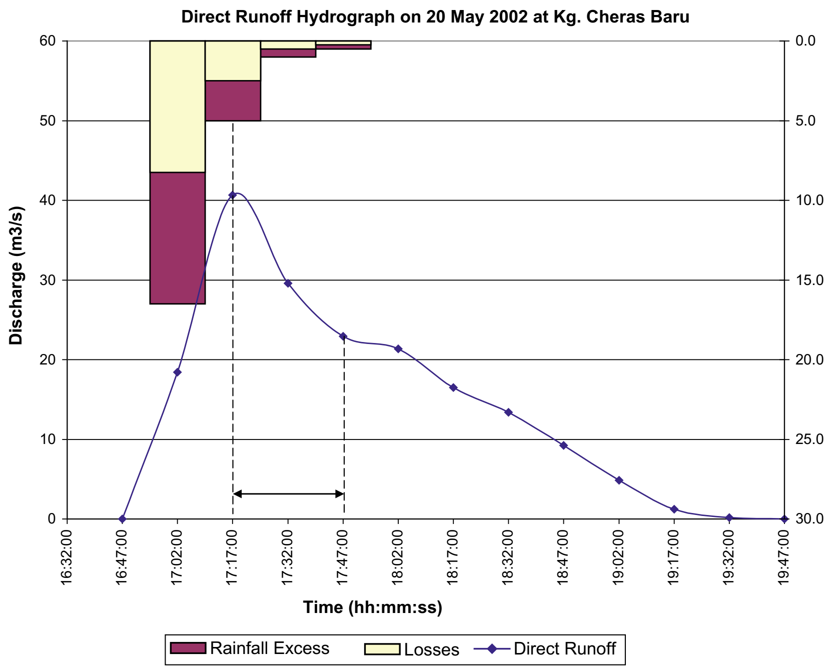

Fig. 53 T_c = 30 min (Kg. Cheras Baru, 20-05-2002)

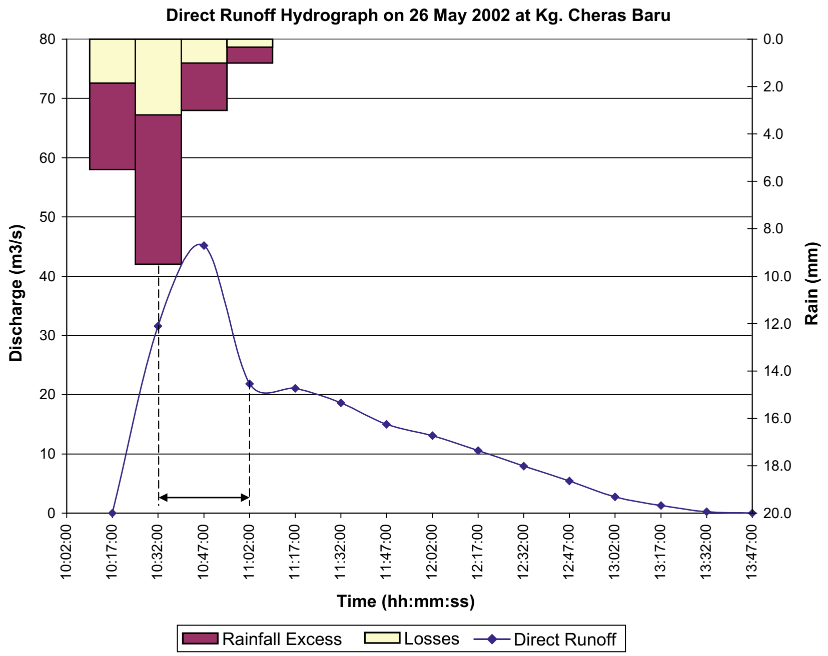

Fig. 54 T_c = 30 min (Kg. Cheras Baru, 26-05-2002)

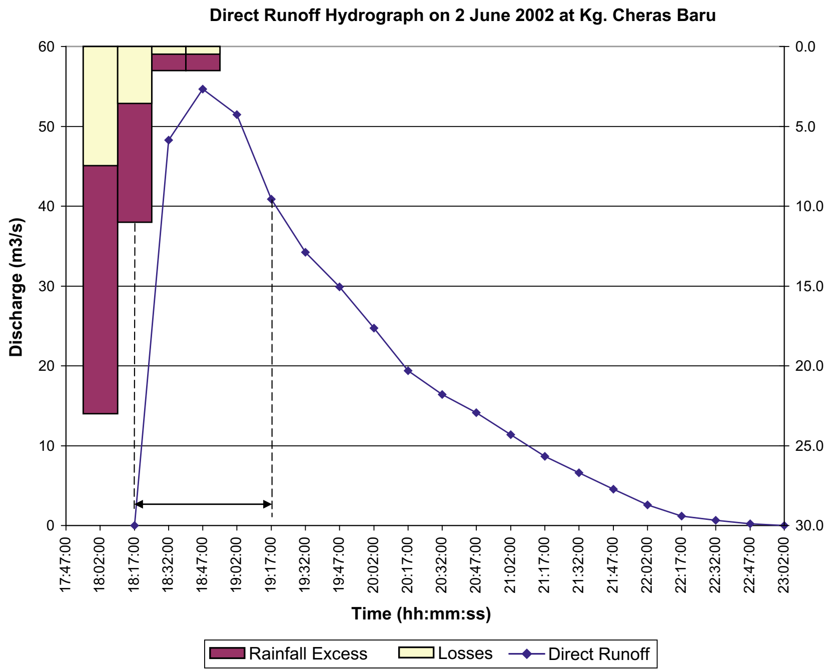

Fig. 55 T_c = 60 min (Kg. Cheras Baru, 02-06-2002)

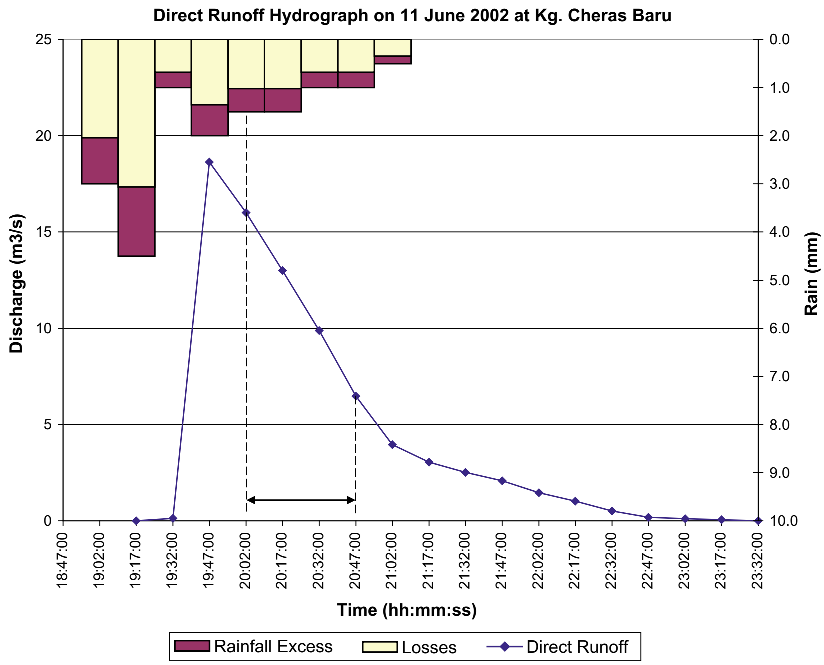

Fig. 56 T_c = 45 min (Kg. Cheras Baru, 11-06-2002)

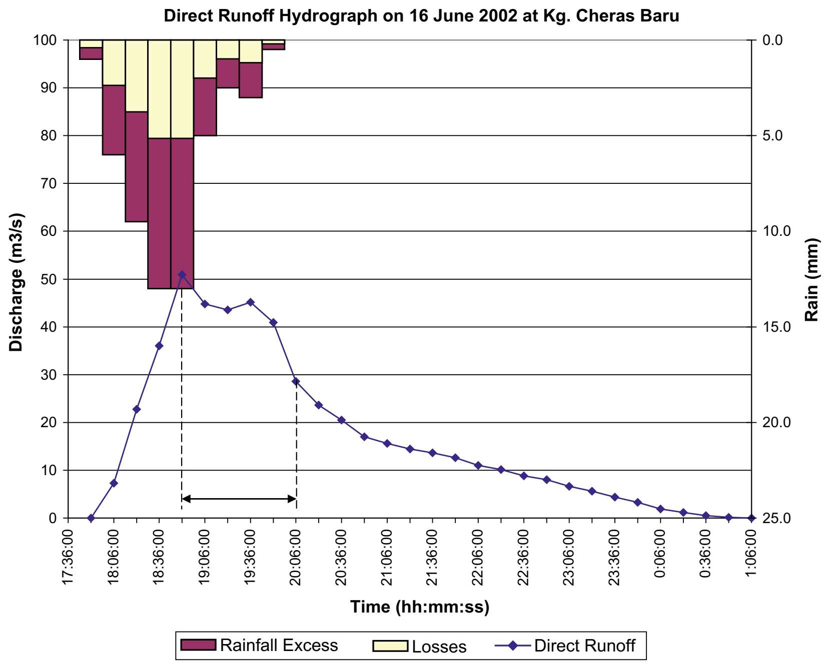

Fig. 57 T_c = 75 min (Kg. Cheras Baru, 16-06-2002)

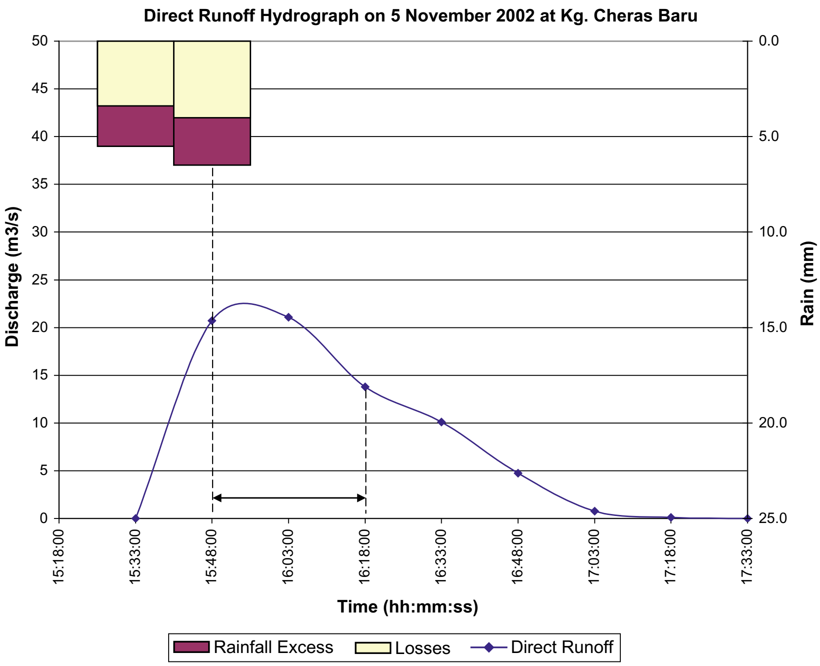

Fig. 58 $T_c = 30$ min (Kg. Cheras Baru, 05-11-2002)

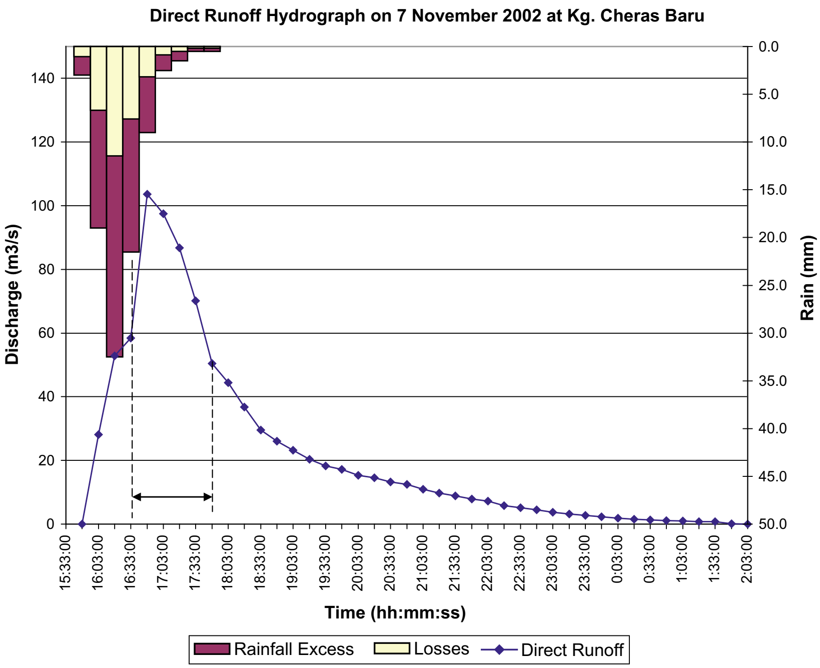

Fig. 59 $T_c = 75$ min (Kg. Cheras Baru, 07-11-2002)

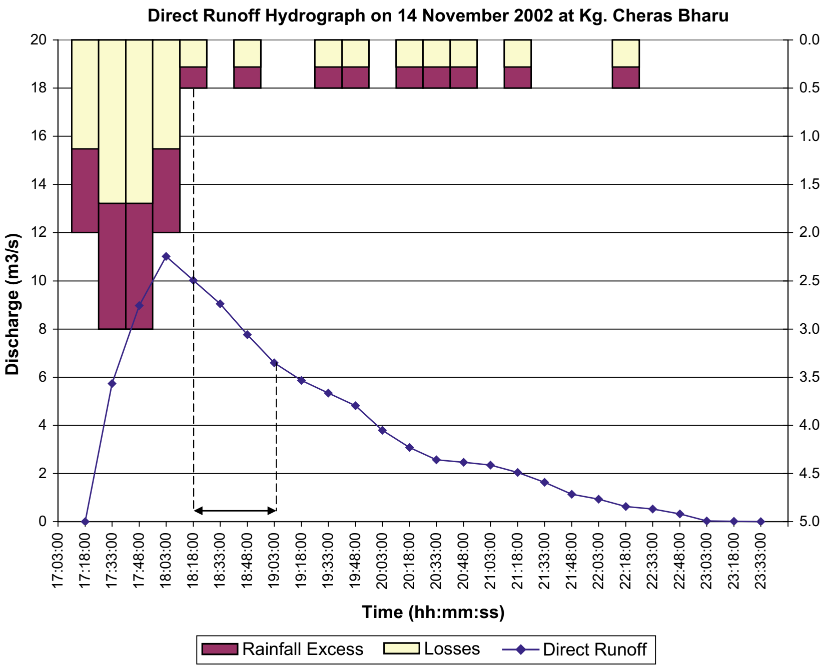

Fig. 60 T_c = 45 min (Kg. Cheras Baru, 14-11-2002)

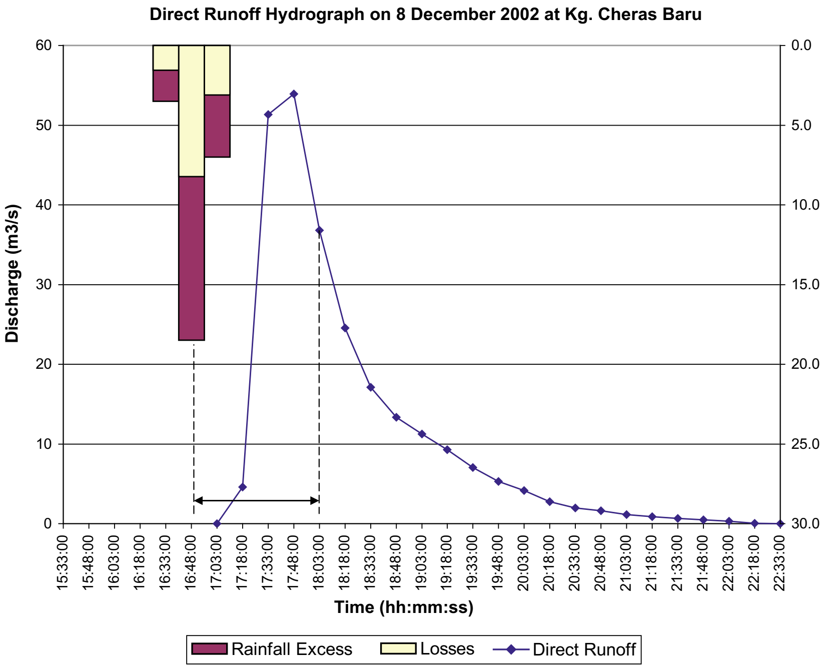

Fig. 61 T_c = 75 min (Kg. Cheras Baru, 08-12-2002)

References

1. Perdikaris J, Gharabaghi B, Rudra R (2018) Reference time of concentration estimation for ungauged catchments. Earth Sci Res 7(2):58. https://doi.org/10.5539/esr.v7n2p58
2. Sharifi S, Hosseini SM (2011) Methodology for identifying the best equations for estimating the time of concentration of watersheds in a particular region. https://doi.org/10.1061/(ASCE)IR.1943-4774.0000373
3. McCuen R, Wong SL, Rawls WJ (1984) Estimating urban time of concentration. J Hydraul Eng 110(7):887–904. ISSN 0733-9429/84/0007-0887. Retrieved from https://ascelibrary.org/doi/pdf/10.1061/%28ASCE%290733-9429%281984%29110%3A7%28887%29
4. DID (2010) Hydrological procedure no. 5 rational method of flood estimation for rural catchments in Peninsular Malaysia, Malaysia. Retrieved from http://h2o.water.gov.my/man_hp1/HP5_2010.pdf
5. Fang X, Thompson DB, Cleveland TG, Pradhan P, Malla R (2008) Time of concentration estimated using watershed parameters determined by automated and manual methods. J Irrig Drain Eng 134(2):202–211
6. Nagy ED, Torma P, Bene K (2016) Comparing methods for computing the time of concentration in a medium-sized Hungarian catchment. Slovak J Civ Eng 24(4):8–14. https://doi.org/10.1515/sjce-2016-0017
7. Salimi ET, Nohegar A, Malekian A, Hoseini M, Holisaz A (2017) Estimating time of concentration in large watersheds. Paddy Water Environ 15(1):123–132. https://doi.org/10.1007/s10333-016-0534-2
8. Almeida IK De, Almeida AK, Ayach JA, Steffen JL, Sobrinho TA (2014) Estimation of time of concentration of overland flow in watersheds: a review. 1(1):661–671
9. Almeida IK De, Almeida AK, Garcia GS, Alves ST (2017). Performance of methods for estimating the time of concentration in a watershed of a tropical region. https://doi.org/10.1080/02626667.2017.1384549
10. Gericke OJ, Smithers JC (2014) Review of methods used to estimate catchment response time for the purpose of peak discharge estimation. Sci J 59(11). https://doi.org/10.1080/02626667.2013.866712
11. Roussel MC, Thompson DB, Fang X, Cleveland TG, Garcia CA (2005) Time-parameter estimation for applicable Texas watersheds. Beaumont, Texas. Retrieved from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.248.6150&rep=rep1&type=pdf
12. Abustan I, Sulaiman AH, Wahid NA, Baharudin F (2008) Determination of rainfall-runoff characteristics in an urban area: Sungai determination of rainfall-runoff characteristics in an urban area: Sungai Kerayong catchment, Kuala Lumpur. In: 11th international conference on urban drainage, Edinburgh, Scotland, UK, pp 1–11
13. Baharudin F (2007) A study on rainfall-runoff characteristics of urban catchment of Sungai Kerayong. Universiti Sains Malaysia. Retrieved from http://Eprints.Usm.My/7772/1/A_Study_On_Rainfall-Runoff_Characteristics_Of_Urban_Catchment_Of_Sungai_Kerayong.Pdf
14. Carter RW (1961) Magnitude and frequency of floods in suburban areas
15. Azizian A (2018) Uncertainty analysis of time of concentration equations based on first-order-analysis (FOA) method. Am J Eng Appl Sci Orig Res Pap. https://doi.org/10.3844/ajeassp.2018.327.341
16. Chen CN, Wong TSW (1993) Critical rainfall duration for maximum discharge from overland plane. J Hydraul Eng 119:1040–1045. ISSN 0733-9429/93/0009. Retrieved from https://ascelibrary.org/doi/pdf/10.1061/%28ASCE%290733-9429%281993%29119%3A9%281040%29
17. NRCS (1986) Urban hydrology for small watersheds. Retrieved from https://www.nrcs.usda.gov/Internet/Fse_Documents/stelprdb1044171.pdf
18. Kirpich ZP (1940) Time of concentration of small agricultural watersheds, vol 6
19. Kerby WS (1959) Time of concentration studies. Civil Engineering
20. FHWA (1984) Drainage of highway pavements hydraulic engineering circular no. 12. Retrieved from https://www.fhwa.dot.gov/engineering/hydraulics/pubs/hec/hec12.pdf

21. Williams GB (1922) Flood discharges and the dimensions of spillways in India 134:321. England (London)
22. Izzard CF, Hicks WI (1946) Hydraulics of runoff from developed surfaces. Highw Res Board Proc 26. Retrieved from https://trid.trb.org/view/103974
23. Morgali JR, Linsley RK (1965) Computer analysis of overland flow. J Hydraul Div 91(3):81–100. Retrieved from https://cedb.asce.org/CEDBsearch/record.jsp?dockey=0013661
24. United States Soil Conservation Service (1975) Urban hydrology for small watersheds
25. Johnstone D, Cross WP (1949) Elements of applied hydrology. Ronald, New York
26. Yen BC, Chow VT (1983) Local design storms. Report
27. Bransby WG (1922) Flood discharge and the dimensions of spillways in India. The Engineer, 321–322. Retrieved from https://drive.google.com/file/d/0Byy0dkN8g_n7YzBOOFRjbmZJS1E/view
28. Gundlach DL (1976) Unit hydrograph parameters versus urbanization. J Irrig Drain Div 102 (3):388–392. Retrieved from https://cedb.asce.org/CEDBsearch/record.jsp?dockey=0025275
29. Wong TSW, Li Y (1998) Assessment of changes in overland time of concentration for two opposing urbanization sequences. Hydrol Sci J 43(1):115–130. https://doi.org/10.1080/02626669809492106
30. ARR (1987) Australia rainfall and runoff. Institution of Engineers Barton, A.C.T., Australia
31. Haktanir T, Sezen N (1990) Suitability of two-parameter gamma and three-parameter beta distributions as synthetic unit hydrographs in anatolia. Hydrol Sci J 35(2):167–184. https://doi.org/10.1080/02626669009492416
32. USDCM (2018) Urban storm drainage criteria manual, vol 1. Retrieved from www.udfcd.org
33. MacKenzie KA (2010) Full-spectrum detention for stormwater quality improvement and mitigation of the hydrologic impact of development. Master thesis, Department of Civil Engineering, University of Colorado Denver
34. Guo JCY, MacKenzie K (2014) Modeling consistency for small and large watershed studies. J Hydrol Eng 19(8):1–7. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000948
35. Arizona DOT (Arizona Department of Transportation) (1993) Highway drainage design manual hydrology final report. Retrieved from https://azdot.gov/docs/business/highway-drainage-design-manual-hydrology
36. Papadakis KN, Kazan MN (1987) Time of concentration in small rural watersheds. In: Proceedings of the ASCE engineering hydrology symposium. Williamsburg, VA: ASCE, 633–638
37. NRCS (2008) National engineering handbook part 630. Engineering
38. Guo JCY, Urbonas B (2008) Consistency between CUHP and rational methods. Retrieved from https://udfcd.org/wp-content/uploads/uploads/resources/technicalpapers/RevisionstoCUHPandRationalMethod2008.pdf
39. MSMA (2012) Urban stormwater management manual for Malaysia, 2nd edn. MSMA