Comparison of salt experiments and empirical time of concentration equations

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The time of concentration (T_c) is one of the most contributing parameters for assessing the response of a catchment to rainfall events and estimating the peak flood in many hydrological models. The aim of this work was to evaluate 36 time of concentration equations based on T_c values obtained based on the salt dilution tracing approach. In addition, hierarchical cluster analysis (CA) was applied to identify the degree of similarity between all the T_c formulas and categorise them into several groups. The findings, based on seven sub-watersheds of the Meime river basin in Iran, demonstrate that the Picking, Pickering, DNOS, California and Kirpich-Ten equations provide reliable estimation of T_c ; the average bias of these formulas was found to be in the range 2.6–15 min while, for all 36 equations, the bias was 2.6–132.8 min. Furthermore, based on CA, all T_c equations were categorised into four overall groups with the maximum similarity within the members of each group.

Notation

A	catchment area (km^2)
A_{imp}	fraction of impervious area (%)
C	runoff coefficient
CN	SCS curve number
D	equivalent diameter of catchment (km)
H	quota difference between the ends of the main channel or longest flow path (m)
H_m	mean altitude of catchment (m)
I	percentage of impervious areas (%)
i_{2y}	two-year rainfall intensity (mm/h)
K	type of surface coefficient in SCS Formula
k	type of surface coefficient in DNOS Formula
L_b	length of watershed along the main channel from the hydraulically most distant point to the outlet (km)
L_c	length of main channel (km)
L_{ca}	mean length starting from concentration spot along the length up to the spot where L_c is perpendicular to the centroid of the catchment (km)
L_{LF}	length of longest flow path for each sub-basin (km)
L_m	length of all streams in watershed
L_t	length of all streams larger than 30 inch in width
N	retardance coefficient
n	Manning's roughness coefficient
p	relation between vegetation cover and total area of basin
R	hydraulic radius (m)

S_b	average slope of watershed (m/m)
S_c	average slope of main channel or longest flow path (m/m)
S_{scs}	maximum capacity of retention (mm)
T_c	time of concentration (h)
$\Delta H_{\text{channel}}$	quota difference between ends of main channel (m)
ΔH_{basin}	mean elevation of catchment (m)
Φ	conductance or channelisation factor

1. Introduction

The time of concentration (T_c) is a concept used in hydrology to measure the response of a watershed to a rain event (Haan *et al.*, 1994). It is defined as the time required for all contributing parts of the catchment to producing runoff (or discharge) at the watershed's outlet (Fang *et al.*, 2008), and is one of the most important parameters for evaluating the response of a catchment (McCuen *et al.*, 1984; Wong, 2009) and estimating peak floods in hydrologic designs. For instance, the geomorphological instantaneous unit hydrograph (GIUH) and kinematic waved (KW)-GIUH models that are used for estimation of peak flood require an accurate estimation of T_c (Azizian and Shokoohi, 2015a, 2015b; Huang *et al.*, 2015). In addition, the Clark unit hydrograph method requires an estimation of T_c in order to calculate the time–area histogram, the time to peak and the peak flood (Dhakal *et al.*, 2014; Sadeghi *et al.*, 2015). Appropriate estimations of T_c can minimise errors in the prediction of design discharges and,

subsequently, flood damage (Bondelid *et al.*, 1982; de Almeida *et al.*, 2014). If the values for T_c are underestimated, they will lead to overestimated values for results related to peak discharge and vice versa (Fang *et al.*, 2008). However, the concept of T_c is highly questioned because there are difficulties in its determination and because it is influenced by the rainfall intensity and the initial moisture conditions of the catchment. There is therefore significant uncertainty about identifying the best T_c method and what best defines its concept (Grisson *et al.*, 2008). Because of the great importance of T_c , there is a huge number of empirical/semi-empirical and analytical T_c equations and each has resulted from studies that have been performed in specific regions. For this reason, researchers and engineers are often confused by the many equations and select a formula without evaluating and comparing its accuracy with other methods (Grimaldi *et al.*, 2012; McCuen *et al.*, 1984; Wong and Asce, 2005).

Several studies have been carried out to address the importance of T_c in hydrological modelling, identify the accuracy of the T_c equations and introduce new approaches for estimating T_c . For example, McCuen *et al.* (1984), Wong and Asce (2005), Fang *et al.* (2008), Sharifi and Hosseini (2011) and Liang and Melching (2012) reviewed, compared and evaluated different empirical/semi-empirical and analytical T_c equations. Moreover, some researchers have focused on developing new approaches for the estimation of T_c or modifying empirical and analytical equations such as the kinematic wave and Morgali-Linsley equations (Baïamonte and Singh, 2015; De Almeida *et al.*, 2016; El-Hames, 2013; Grimaldi and Petroselli, 2015; Manoj *et al.*, 2013; Ogbonna, 2004). There are many approaches for estimating a catchment's T_c , but the major ones are as follows.

- (a) Estimating the time span between the end (or centre) of effective rainfall and the inflection point of the hydrograph falling limb (McCuen, 2009; Singh, 1988).
- (b) Using empirical equations that depend on geomorphological parameters (McCuen *et al.*, 1984; Singh, 1988) and rainfall attributes (in some cases). The equations that fall into this category are mainly based on regression analysis and have been developed only for specific catchments (Fang *et al.*, 2007).
- (c) Injecting salt dilution or tracer soluble in the upstream of a river and measuring the travel time in the river's downstream (Dingman, 2002).

Results based on either of these approaches will not always be unique and each has some benefits and disadvantages. In other words, a global exact method for estimating T_c is not available and hence the true value of this parameter can never be determined (McCuen *et al.*, 1984). Therefore, for a specific region, one can concentrate on selecting the most accurate formula(s) and modifications if necessary (Sharifi and Hosseini, 2011). In

contrast to many research studies, in this work, the third approach was adopted to estimate T_c , which was then used as a reference value for an assessment of empirical/semi-empirical T_c equations. Specifically, the aim of this work was to

- evaluate 36 empirical/semi-empirical T_c equations by using the salt injection approach
- classify all 36 T_c equations by using hierarchical cluster analysis (CA) to distinguish and categorise the most similar equations.

2. Method

2.1 Study area

The study area, the Meime river basin (MRB), is part of Dehloran province in Iran and its elevation ranges from 1115 to 2244 m above mean sea level. The total area and perimeter of the MRB are about 83.92 km² and 47.6 km, respectively. The MRB lies between the coordinates 33°12'34"N and 33°19'03"N latitude and 46°49'44"E and 46°58'26"E longitude. The climate is semi-arid (or steppe climate) and the annual rainfall varies from 170 to 648 mm with an average annual rainfall of 291 mm. The daily mean temperature of this watershed varies in the range 12.3–38.7°C and the mean relative humidity varies from 18% (August and July) to a maximum of 66% (January). To extract the required geomorphological parameters for all the T_c equations, a 1:25 000 scale topographic map was used. This map was geo-referenced by Mercator's (UTM, time zone 38) transverse projection within QGIS (previously known as Quantum GIS) (a cross-platform free and open-source desktop geographic information system (GIS) application), and then a digital elevation model (DEM) with 50 m resolution was obtained. The location of the MRB and its DEM with a resolution of 50 m is shown in Figure 1.

2.2 Approach for obtaining the reference value of T_c

The methodology used to obtain the 'reference' T_c values was based on measurement of the travel time of a salt tracer. The salt dilution method is a simple and robust method for flow measurement and estimation of T_c , which does not require a hydrologist to enter the deepest sections of a river. This method has been used for flow measurements in several applications and other studies (e.g. Church and Kellerhals, 1970; Hudson and Fraser, 2002; Spence and McPhie, 1997). The basis of the method is the conservation of mass of a tracer substance before and after dilution by a flowing stream. The concentration of the tracer measured downstream after it has become uniformly distributed across the channel is related to the discharge of the stream – the lower the concentration the greater the discharge. Table salt (sodium chloride (NaCl)) is commonly used as the tracer and its concentration is measurable with high sensitivity (Drost, 1989; Kumar and Nachiappan, 2000; Moore, 2004; Tazoil, 2011). When using sodium chloride as the tracer, electrical conductivity (EC) is

Figure 1. Location and DEM of the study area (map data © Google, AutoNavi, Basarsoft, Mapa GISrael, ORION-ME; imagery © Landsat, Data SIO, NOAA, US Navy, GEBCO)

substituted for mass concentration. The time between the entry of sodium chloride in the upstream and the time of the peak EC in the downstream is the travel time of flow (or T_c) in that segment. The summation of travel times in the consecutive segments defines the catchment's T_c and in this study (see Figure 2) is considered as the 'reference' T_c value. The tracer measurements were carried out over 3 d without any rainfall. Measuring tracer values on a rainy day imposes several difficulties, such as measuring the peak EC accurately and the entry of other pollutions or mudflows from overland parts or tributaries, which would affect the dosage of tracer in the water. In this research, the sodium chloride dilution was made to enter the upstream of each stream suddenly and the variation of EC over time was measured by means of a chronometer in the downstream.

After measuring the travel time for each segment, the geomorphological parameters used in the selected equations needed to be extracted. In this study, the D8 flow tracing algorithm (O'Callaghan and Mark, 1984) in the QGIS environs was used to extract the streams' network and geomorphological features. The geomorphological parameters of the seven sub-basins of the Meime watershed are summarised in Tables 1 and 2.

2.3 Empirical/semi-empirical T_c equations

All T_c equations are based on four types of input – slope, catchment size, flow resistance and rainfall attributes. These characteristics are either for the overland flow parts of the

watershed, the pipe system or the channel flow system (McCuen *et al.*, 1984). Therefore, T_c formulas can be categorised on the basis of their input requirements and the dominant flow regime. Because the channels and drainage network in the MRB are well-developed, channel flows are predominant and overland flows play a minor role in runoff production. For example, in sub-3, two points (with the greatest distance to the stream network) were selected to measure the travel time of overland flows and the results showed that the maximum T_c value was about 3.3 min. This value of overland T_c in sub-3 relative to the longest flow path's T_c (42.5 min) was small (less than 8%) and could thus be ignored.

Equations for estimating T_c that include channel features should be used when channel flow makes a significant contribution to the total travel time of runoff (McCuen *et al.*, 1984). Thus, in order to compare the empirical equations and the sodium chloride tracer method used in this study, only T_c formulas that fall into the channel flow regime were selected. As shown in Table 3, T_c equations depend on many coefficients, variables and physiographic features. The values of these coefficients and a summary of the watershed characteristics are given in Table 4.

2.4 Methodology of evaluating and identifying the best T_c equations

Identifying the best T_c formulas needs reasonable goodness-of-fit criteria. There is a huge number of criteria when it comes to

Figure 2. Locations of salt injection points in each river segment

comparing observed and estimated values and each of them gives different results. Similar to the study of Sharifi and Hosseini (2011), a ranking-based selection procedure was developed in this research. The mean error (ME), mean relative error (MRE) and root mean square error (RMSE) were selected as assessment criteria. The difference in the means of the estimated and reference T_c values can be used as a measure of the actual bias; a positive value of the ME indicates over-prediction while a negative value illustrates that the estimated value is less than the reference T_c . The ME for an equation can be dominated by errors in large T_c values (McCuen *et al.*, 1984). Thus, standardised bias statistics (SBS or MRE) were used to indicate the bias in each T_c formula. All the T_c equations were ranked based on each criterion and these were then summed up to give the overall ranking. These indices were obtained using

$$1. \quad RMSE = \sqrt{\frac{\sum_{i=1}^{N_b} (T_{c_{est}} - T_{c_{obs}})^2}{N_b}}$$

$$2. \quad ME = Bias = \frac{1}{N_b} \sum_{i=1}^{N_b} (T_{c_{est}} - T_{c_{obs}})$$

$$3. \quad MRE = SBS = \frac{1}{N_b} \sum_{i=1}^{N_b} \frac{(T_{c_{est}} - T_{c_{obs}})}{T_{c_{obs}}}$$

in which N_b is the number of sub-basins, $T_{c_{est}}$ is the estimated T_c value based on empirical equations and $T_{c_{obs}}$ is the reference T_c value.

2.5 Classification of all T_c equations using CA

CA (or clustering) is the task of grouping a set of objects in such a way that objects in the same group (called a cluster) are more similar and hold common features. CA is one of a class of techniques that classifies cases into groups that are relatively homogeneous within themselves and relatively heterogeneous between each other (Lowrimore and Manton, 2016). This analysis is commonly used in many research fields such as geomorphology (Melchiorre *et al.*, 2008), environmental engineering (Hatvani *et al.*, 2011) and water resources (Li *et al.*, 2012; Yoo *et al.*, 2011). There are two main methods – hierarchical and non-hierarchical CA – and, for simplicity, the hierarchical method was used in this study. Hierarchical CA requires the researcher to establish a prior number of clusters in the final solution (Ratrou, 2010). If there is uncertainty about the total number of clusters in the dataset, the analysis must be re-run for each possible solution. In this situation, hierarchical clustering is preferred as it inherently allows one to compare the clustering result with an increasing number of clusters; no

Table 1. Measured T_c values and geomorphological parameters of each sub-basin

Sub-basin	Reach number	$\Delta H_{\text{channel}}$: m	Horizontal distance: m	Velocity: m/s	Channel length: km	Channel slope: %	Measured T_c : min
Sub-1	1	26	730	2.0	1.21	3.56	9.60
	2	40	1350	2.1	2.24	3.96	16.20
	3	40	1130	2.6	1.88	3.54	13.20
	4	40	1760	2.4	2.92	2.27	22.20
	5	40	700	2.2	1.16	5.71	7.20
	6	40	700	2.1	1.17	5.71	7.20
	7	80	400	2.0	0.68	20.00	3.50
	Total				11.26		79.10
Sub-2	1	26	670	2.3	0.67	3.88	5.17
	2	40	540	2.7	0.59	7.41	3.34
	3	60	720	3.2	0.72	8.33	3.95
	4	100	780	3.1	0.79	12.82	3.65
	5	60	680	2.5	0.68	8.82	3.95
	6	80	770	3.0	0.77	10.39	3.95
	7	100	600	3.1	0.67	16.67	2.74
	8	200	610	4.1	0.64	32.79	2.13
	9	140	390	5.1	0.65	35.90	1.52
	Total				6.18		30.40
Sub-3	1	42	830	2.6	0.83	5.60	5.62
	2	40	710	2.2	0.71	5.63	4.94
	3	80	780	3.1	0.78	10.26	4.28
	4	80	700	3.2	0.71	11.43	3.95
	5	100	860	3.1	0.87	11.63	4.61
	6	80	870	3.2	0.88	9.20	4.94
	7	80	710	3.3	0.71	11.27	3.95
	8	60	780	2.4	0.78	7.69	4.94
	9	140	760	3.3	0.77	18.42	3.62
	10	120	350	5.0	0.59	34.29	1.65
	Total				7.63		42.50
Sub-4	1	44	800	2.6	0.83	5.50	5.24
	2	60	850	2.9	0.85	7.06	4.93
	3	80	940	3.2	0.94	8.51	4.93
	4	80	730	3.3	0.73	10.96	3.71
	5	120	680	3.4	0.69	17.65	3.38
	6	180	730	4.5	0.75	24.66	2.77
	7	40	640	2.5	0.65	6.25	4.31
	8	40	710	2.6	0.73	5.63	4.62
	9	80	790	3.0	0.79	10.13	4.32
	10	180	840	4.2	0.86	21.43	3.39
	Total				7.82		41.60
Sub-5	1	41	650	2.5	0.43	6.31	2.84
	2	40	570	2.6	0.38	7.02	2.43
	3	40	780	2.5	0.52	5.13	3.45
	4	40	700	2.5	0.46	5.71	3.04
	5	80	630	3.5	0.43	12.70	2.03
	6	120	610	3.8	0.41	19.67	1.82
	7	140	650	4.2	0.44	21.54	1.74
	8	140	640	4.2	0.43	21.88	1.72
	9	80	850	3.1	0.57	9.41	3.04
	10	80	940	3.2	0.63	8.51	3.25
	11	80	500	3.5	0.34	16.00	1.62
	12	140	420	4.0	0.29	33.33	1.22
	Total				5.33		28.20

(continued on next page)

Table 1. Continued

Sub-basin	Reach number	$\Delta H_{\text{channel}}$: m	Horizontal distance: m	Velocity: m/s	Channel length: km	Channel slope: %	Measured T_c : min
Sub-6	1	22	630	2.2	0.51	3.49	3.80
	2	40	930	2.7	0.75	4.30	4.68
	3	40	750	2.8	0.61	5.33	3.57
	4	40	690	2.8	0.56	5.80	3.34
	5	40	690	2.8	0.56	5.80	3.34
	6	100	660	4.0	0.54	15.15	2.23
	7	80	710	3.6	0.58	11.27	2.67
	8	100	700	3.9	0.57	14.29	2.45
	9	200	760	4.7	0.64	26.32	2.27
	10	80	780	3.6	0.63	10.26	2.90
	11	60	650	3.3	0.53	9.23	2.68
	12	80	730	3.7	0.59	10.96	2.67
	13	160	720	4.5	0.60	22.22	2.20
Total					7.67		38.80
Sub-7	1	5	600	1.4	0.41	0.83	4.80
	2	20	930	2.3	0.65	2.15	4.80
	3	20	930	2.2	0.64	2.15	4.80
	4	20	880	2.3	0.61	2.27	4.40
	5	20	950	2.0	0.66	2.10	5.40
	6	20	1070	2.2	0.74	1.87	5.50
	7	20	870	2.3	0.60	2.30	4.40
	8	20	750	2.1	0.52	2.67	4.20
	9	20	1150	2.2	0.79	1.74	6.00
	10	20	760	2.2	0.52	2.63	3.90
	11	40	1070	2.9	0.74	3.74	4.20
	12	20	650	2.0	0.45	3.08	3.70
	13	40	1130	2.9	0.78	3.54	4.50
	14	20	1060	2.3	0.73	1.89	5.40
	15	40	1100	2.9	0.76	3.64	4.40
	16	40	780	3.1	0.54	5.13	2.90
	17	100	620	2.8	0.43	16.13	2.60
Total					10.57		75.90

Table 2. T_c and geomorphological characteristics of the MRB sub-basins

Sub-basin	Area: km ²	Main channel length: km	ΔH_{basin} : m	$\Delta H_{\text{channel}}$: m	Basin slope: m/m	Channel slope: m/m	Observed T_c : min
Sub-1	16.26	11.26	681	292	0.060	0.026	79.1
Sub-2	12.01	6.18	831	806	0.134	0.130	30.4
Sub-3	8.82	7.63	834	822	0.109	0.100	42.5
Sub-4	10.22	7.82	907	892	0.116	0.110	41.6
Sub-5	9.62	5.33	1029	1021	0.193	0.191	28.2
Sub-6	13.83	7.67	1126	1032	0.146	0.134	38.8
Sub-7	13.16	10.57	578	506	0.050	0.040	75.9

decision about the final number of clusters needs to be made beforehand. The first step a researcher must take is to determine the statistic that will be used to calculate the distance or similarity between cases. The most commonly used distance measure is the squared Euclidean distance, given by

$$4. \quad d = \sum_{i=1}^z (a_i - b_i)^2$$

in which a_i and b_i refer to the two cases being compared for the variable i and z is the total number of variables included in the analysis (Ratrou, 2010). If the value of d is close to zero, the more similarity exists between two cases.

Finally, to select the optimal number of clusters in the dataset, cluster validity indices should be calculated. There are several validity indices, including the root mean square standard deviation (RMSSTD) of all the variables within each cluster,

Table 3. Summary of the selected T_c equations

Name	Reference	Equation	Comments
1 Arizona DoT	ADoT (1993)	$T_c = 0.0097956A^{0.1}(1000L_b)^{0.25}L_{ca}^{0.25}S_b^{-0.2}$	Data of agricultural basins
2 Basso	Eslamian and Mehrabi (2005)	$T_c = 0.957L_b^{1.155}H_m^{-0.385}$	Data not available
3 Bransby Williams	Moth (1998)	$T_c = 0.605L_c(100S_c)^{-0.2}A^{-0.1}$	Specially recommended for rural basins
4 California	CDH (1960)	$T_c = 0.95L_{LF}^{1.155}H^{-0.385}$	Data of small mountain basins in USA
5 Carter	Carter (1961)	$T_c = 0.0977L_b^{0.6}S_b^{-0.3}$	Data of an urban basin in USA ($A < 20.72 \text{ km}^2$; $S < 0.005$)
6 Chow <i>et al.</i>	Chow <i>et al.</i> (1988)	$T_c = 0.1602L_c^{0.64}S_c^{-0.32}$	Data of 20 rural basins in USA ($0.01\text{--}18.5 \text{ km}^2$; $0.0051 < S < 0.09$)
7 Corps of Engineers	Linsley <i>et al.</i> (1977)	$T_c = 0.191L_c^{0.76}S_c^{-0.19}$	Data of 25 rural basins in the USA ($A \leq 12 \text{ km}^2$)
8 Desbordes	Silveira (2005)	$T_c = 0.0869A^{0.3039}S_b^{-0.3832}A_{imp}^{-0.4523}$	Data not available
9 DNOS	Silveira (2005)	$T_c = 0.419k^{-1}A^{0.2}L_c^{0.2}S_c^{-0.4}$	Data of six rural basins in USA ($A < 0.45 \text{ km}^2$; $0.03 < S < 0.1$)
10 Dooge	Dooge (1973)	$T_c = 0.365A^{0.41}S_c^{-0.17}$	Data of ten rural basins in Ireland ($145\text{--}948 \text{ km}^2$)
11 Epsey	Hotchkiss and McCallum (1995)	$T_c = 6.89L_c^{0.36}S_c^{-0.18}$	Data of 11 rural basins in USA
12 Epsey–Winslow	McCuen (1998)	$T_c = 0.45\Phi L_c^{0.29}S_c^{-0.11}I^{-0.6}$	Data of 17 rural and urbanised basins ($1\text{--}35 \text{ mi}^2$ ($\approx 3\text{--}90 \text{ km}^2$))
13 Eagleson	Eagleson (1962)	$T_c = 0.275nL_cR^{-0.667}S_c^{-0.5}$	Calibrated from data for catchments less than 8 mi^2 ($\approx 21 \text{ km}^2$)
14 FAA	FAA (1970)	$T_c = 0.3788(1.1 - C)L_{LF}^{0.5}S_b^{-0.332}$	Data of airports' drainage
15 Flavell	Flavell (1983)	$T_c = 2.31A^{0.54}$	Obtained from observed times of hydrograph rise on basins in the south west of Western Australia
16 Ribeiro	Ribeiro (1961)	$T_c = 0.267(1.05 - 0.2p)^{-1}L_cS_c^{-0.04}$	Data of seven rural basins in USA and a rural basin in India ($A < 19\,000 \text{ km}^2$; $0.03 < S < 0.1$)
17 Giandotti	Giandotti (1934)	$T_c = (4\sqrt{A} + 1.5L_c)/(0.8\sqrt{H_m})$	Data of basins in Italy ($170\text{--}70\,000 \text{ km}^2$)
18 Haktanir–Sezen	Haktanir and Sezen (1990)	$T_c = 0.7473L_{LF}^{0.841}$	Data of ten basins in Turkey ($11\text{--}9867 \text{ km}^2$)
19 Johnstone–Cross	Johnstone and Cross (1949)	$T_c = 0.4623L_{LF}^{0.5}S_b^{-0.5}$	Data of 19 rural basins in USA ($64.8\text{--}4206.1 \text{ km}^2$)
20 Kerby–Hathaway	Kerby (1959); Hathaway (1945)	$T_c = 0.606N^{0.47}L_{LF}^{0.47}S_b^{-0.235}$	Analysis of overland flow in experimental surfaces ($L_{LF} < 0.37 \text{ km}$)
21 Kirpich–Ten	Kirpich (1940)	$T_c = 0.0653L_{LF}^{0.77}S_b^{-0.385}$	Data of small watersheds in Tennessee and Pennsylvania ($0.004\text{--}0.453 \text{ km}^2$; $0.03 < S < 0.1$)
22 Kirpich–Pen	Kirpich (1940)	$T_c = 0.01104L_{LF}^{0.77}S_b^{-0.5}$	
23 McCuen <i>et al.</i>	McCuen <i>et al.</i> (1984)	$T_c = 2.2535i_{2y}^{-0.7164}L_{LF}^{0.5552}S_c^{-0.207}$	Starting from data of 48 urban basins in USA ($0.4\text{--}16 \text{ km}^2$; $0.0007 < S < 0.03$)
24 Pasini	Pasini (1914)	$T_c = 0.108A^{0.332}L_c^{0.332}S_c^{-0.5}$	Data of rural basins in Italy
25 Pickering	Mata-Lima <i>et al.</i> (2007)	$T_c = 0.9482L_c^{1.155}H^{-0.385}$	Equivalent to Kirpich equation
26 Picking	Silveira (2005)	$T_c = 0.0883L_c^{0.667}S_c^{-0.332}$	Data of rural basins
27 Pilgrim–McDermott	Pilgrim and McDermott (1982)	$T_c = 0.76A^{0.38}$	Developed from 96 basins in eastern New South Wales
28 SCS-lag	Mockus (1961)	$T_c = 0.057[(1000/CN) - 9]^{0.7}L_{LF}^{0.8}S_b^{-0.5}$	Data of 24 rural basins in USA ($A < 8 \text{ km}^2$)
29 SCS-ave velocity	NRCS (1972, 1986)	$T_c = 0.278 \sum L_c/KS_c^{0.5}$	Method relates watershed slope and surface to flow velocity
30 Simas–Hawkins	Simas and Hawkins (2002)	$T_c = 0.322A^{0.594}L_c^{-0.594}S^{-0.15}S_{scs}^{0.312}$	Data of 168 basins in USA ($0.001\text{--}14 \text{ km}^2$)
31 Schaake <i>et al.</i>	Schaake <i>et al.</i> (1967)	$T_c = 0.0828L_c^{0.24}S^{-0.16}A_{imp}^{-0.26}$	Data not available
32 Sheridan	Sheridan (1994)	$T_c = 2.20L_{LF}^{0.92}$	Nine flatland watersheds located in Georgia and Florida, USA ($2.62\text{--}334.34 \text{ km}^2$)

(continued on next page)

Table 3. Continued

Name	Reference	Equation	Comments
33 Temez	Temez (1978)	$T_c = 0.3 L_c^{0.76} S_c^{-0.19}$	Data of natural basins in Spain
34 Van Sickle	Van Sickle (1962)	$T_c = 0.0081 L_t^{0.13} L_m^{0.13} S^{-0.065}$	Calibrated from data collected in Houston, USA, with drainage areas less than 36 mi ² (≈93 km ²)
35 Ventura	Mata-Lima et al. (2007)	$T_c = 4 A^{0.5} L_c^{0.5} H^{-0.5}$	Data of rural basins in Italy
36 Williams	Williams (1922)	$T_c = 0.272 A^{0.4} L_b D^{-1} S_b^{-0.2}$	Data of basins in India ($A < 129.5$ km ²)

Table 4. Summary of adopted values of the coefficients and watershed characteristics

Watershed characteristics	Average	Standard deviation	Range		CoV
			Minimum	Maximum	
Area: km ²	12.00	2.63	8.82	16.26	0.22
Longest flow path: km	10.06	3.54	7.43	14.35	0.23
Basin slope: %	11.54	4.90	5.00	19.30	0.43
Main channel length: km	8.07	2.16	5.33	11.26	0.27
Main channel slope: %	10.44	5.70	2.60	19.10	0.54
Coefficient Φ (Epsey–Winslow)	0.24	0.13	0.14	0.36	0.53
SCS curve number	73.00	6.20	67.00	78.00	0.05
Two-year rainfall intensity: mm/h ^a	8.62	1.65	6.50	9.50	0.19
Coefficient k (DNOS)	3.25	1.13	2.56	4.85	0.35
Coefficient C (FAA)	0.36	0.11	0.25	0.42	0.30
Coefficient N (Kerby–Hathaway)	0.20	0.09	0.15	0.31	0.45
Manning's coefficient	0.016	0.01	0.01	0.029	0.63
Percentage of impervious area: %	7.00	2.71	4.20	9.30	0.39
Coefficient p (Ribeiro)	0.34	0.14	0.23	0.37	0.42

^aAccording to variations of temporal rainfall pattern due to climate change in the study area, the rate of rainfall intensity varies between 6.50 and 9.50 mm/h

Dunn's index, Davies–Bouldin's index and the pseudo-F index (Milligan and Cooper, 1985). In this study, the RMSSTD index was used for validation of hierarchical CA. This index determined by calculating the within-group sum of squares of each cluster and normalising it by the product of the number of elements in the cluster and the number of variables (Sharma, 1995). The RMSSTD index is given by

$$5. \quad \text{RMSSTD} = \sqrt{W_k / [v(N_z - 1)]}$$

where W_k is the within-group sum of squares of cluster k , N_z is the number of elements in cluster z and v is the number of variables (the variable used in this study was the T_c value obtained based on 36 equations). This index calculates at each step of the hierarchical algorithm a measure of homogeneity of the clusters. In each step, the RMSSTD index is compared with the previous value and if the difference between two steps is lower than 5%, this will be the optimum number of clusters.

3. Results and discussion

3.1 Identifying the best T_c equations

The equations listed in Table 3 were used to estimate T_c for all the sub-basins of the MRB. The ME and MRE

values are summarised in Table 5. The results indicate that the T_c formulas showed significantly different values of ME (or bias). Five of the equations – the Picking, Pickering, DNOS, California and Kirpich-Ten equations – provided relatively small biases, had the highest overall rankings and gave accurate T_c estimations. The maximum values of the MRE and ME for these equations were 14.4% and 6.05 min, respectively, and it can be concluded that these equations are the most appropriate for estimating T_c in the Meime watershed. The development conditions (restrictions) of the DNOS, Kirpich-Ten and Pickering equations were very similar to each other. As summarised in Table 3, the DNOS, Kirpich-Ten and Pickering methods were developed for small or rural basins of the USA. The flow path slopes and catchment areas used in the development of these formulas were 0.03–0.1 and <0.45 km², respectively. This similarity in development conditions leads to similarities in T_c estimations.

Conversely, the Espey, Flavell, Haktanir–Sezen, Sheridan and Simas–Hawkins equations, due to having the lowest overall rankings, did not result in reasonable estimations. The considerable biases in these equations are certainly the result of one or more reasons.

Table 5. Rank and correction factors of the selected equations

Equation	Goodness-of-fit indices						Sum of ranks
	RMSE: h	Rank	ME or bias: min	Rank	MRE or SBS: %	Rank	
Arizona DoT	0.58	11	−31.3	11	−63.4	11	33
Bransby Williams	1.88	29	105.9	32	223.0	33	94
Basso	0.28	7	16.3	8	35.8	9	24
California	0.17	4	5.9	3	11.0	3	10
Carter	0.28	8	−13.9	7	−26.0	6	21
Corps of Engineers	0.75	16	43.3	16	95.6	18	50
Desbordes	0.87	21	50.0	22	111.3	21	64
DNOS	0.13	2	5.9	4	14.4	5	11
Dooge	0.75	17	44.5	18	109.4	20	55
Eagleson	0.22	6	−11.8	6	−30.6	8	20
Epsey	22.59	36	132.8	36	295.6	36	108
Epsey–Winslow	0.80	19	−44.0	17	−90.8	15	51
FAA	0.76	18	43.1	15	92.6	16	49
Flavell	8.03	34	79.3	25	113.2	23	82
Gianfanti	0.82	20	48.5	21	112.8	22	63
Haktanir–Sezen	3.54	33	109.8	35	274.1	35	103
Johnstone–Cross	1.74	28	100.9	31	221.7	32	91
Kerby–Hathaway	0.58	12	34.4	12	79.2	14	38
Kirpich–Pen	0.63	13	−35.5	13	−75.2	12	38
Kirpich–Ten	0.16	3	6.05	5	11.3	4	12
McCuen <i>et al.</i>	1.66	26	97.3	29	215.6	31	86
Pasini	1.23	24	62.4	23	122.6	24	71
Pickering	0.17	5	5.8	2	10.9	2	9
Picking	0.07	1	2.61	1	6.2	1	3
Pilgrim–McDermott	1.17	23	68.6	24	174.8	25	72
Ribeiro	1.63	25	95.3	27	211.7	30	82
Schaake <i>et al.</i>	0.41	9	−19.9	10	−36.3	10	29
SCS-lag	3.12	32	98.6	30	187.8	26	88
SCS-ave velocity	0.48	10	17.7	9	29.4	7	26
Sheridan	14.51	35	85.0	26	188.9	27	88
Simas–Hawkins	2.67	31	108.6	34	188.9	28	93
Temmez	1.66	27	95.5	28	207.2	29	84
Van Sickle	0.72	15	−45.7	19	−94.9	17	51
Chow <i>et al.</i>	0.65	14	35.9	14	75.7	13	41
Ventura	0.90	22	46.2	20	95.6	19	61
Williams	1.88	30	106	33	223.2	34	97

Firstly, dependence on only one parameter and limitations of the T_c equations reduce the applications of T_c equations to other catchments. For example, the Flavell and Haktanir–Sezen equations only depend on the river length whereas the Sheridan formula is only based on catchment area. In addition, in all the T_c equations that contain the river length parameter, the T_c value increases as river length increases and vice versa but, in the Simas–Hawkins equation, the relation between T_c and river length parameter is reversed.

Secondly, the T_c equations may have been calibrated for a limited range of input parameters that differ substantially from the values of the study area. For instance, the Sheridan and Haktanir–Sezen' formulas were developed for large and very large catchments, while the size of the Meime watershed is relatively small.

Thirdly, the empirical coefficients (most of them are land cover-related coefficients) may reflect regional effects, which

make them inappropriate to use in other regions. For example, the Pasini' formula was based on data from specific watersheds in Italy and the Ribeiro' equation was developed based on data obtained from eight rural basins in the USA and India. Therefore, the empirical coefficients (constant or exponent coefficients) in these formulas may be unusable for regions similar to the MRB.

Any of these reasons may lead to significant biases in the T_c equations and the low performances are an indication that the T_c formulas are sensitive and should be evaluated or corrected before being used for other locations.

3.2 Classification of the T_c equations

All the T_c equations were classified based on Euclidean distance and the Ward method. Using Equation 5, the RMSSTD index was calculated for all possible numbers clusters. As shown in Figure 3, the RMSSTD decreased with the number of clusters and remained almost constant after a specific

Figure 3. Variation of RMSSTD with number of clusters

number, which indicates the optimal number of clusters for classifications. In this study, five clusters were accepted for classification of the T_c equations. Figure 4 shows the clustering diagram generated based on hierarchical CA with an added line indicating the optimal stopping point of the clustering procedure.

Based on the most similarity, the following five clusters were obtained.

- Cluster 1. This cluster includes nine equations with the highest similarity. One of the most important factors for this similarity is related to the fact that all of these equations were developed for rural or very small catchments. For instance, the SCS-lag/Ribeiro (USA) and Ventura/Pasini (Italy) formulas were developed for rural catchments. In other words, the conditions for the development of the equations in cluster 1' were very similar to each other. Moreover, investigations of the geomorphological parameter exponents of all the equations in this cluster show that there is a downward trend in the curve of flow path slope and river length exponents. It can be concluded from Figure 5(a) that, by increasing the river length exponent from 0.22 to 0.78, the slope exponent decreases from -0.06 to -0.38. Meanwhile, statistical analyses reveal that the minimum, maximum and average values of T_c in this cluster are about 5.04, 7.80 and 6.35 h, respectively (Table 6). The coefficient of variation (CoV) of this cluster is less than that of the other clusters, with a value of about 14.5%.
- Cluster 2. This cluster contains seven equations with the highest similarity. Most of the equations in this cluster are based on data obtained from agricultural, rural and small urban catchments in the USA. In contrast to cluster 1, there is an upward trend between the river length and flow path slope exponents, as shown in Figure 5(b). In this

Figure 4. Clustering diagram with line added indicating optimal number of clusters

Figure 5. Relation between slope and river length exponents: (a) cluster 1; (b) cluster 2; (c) cluster 3

Table 6. Clustered T_c equations and their statistical parameters

Cluster	Equation	Min: h	Mean: h	Max: h	Standard deviation: h	CoV: %
1	Ribeiro, Williams, Bransby Williams, Pasini, Temez, Ventura, SCS-lag, Johnstone-Cross, McCuen <i>et al.</i>	5.04	6.35	7.80	0.92	14.5
2	Carter, Papadakis-Kazan, Epsey-Winslow, Van Sickle, Arizona DoT, Kirpich-Pen, Schaake <i>et al.</i>	0.10	0.69	1.43	0.50	72.3
3	Chow <i>et al.</i> , Giandotti, FAA, California, Pickering, Kirpich-Ten, Kerby-Hathaway, Basso, DNOS, Eagleson, Picking, Desbordes, Pilgrim-McDermott, SCE-ave velocity, Dooge, Corps of Engineers	2.14	3.12	4.18	0.46	21.8
4–5	Haktanir-Sezen, Simas-Hawkins, Epsey, Sheridan, Flavell	9.46	24.18	38.6	14.17	58.6

cluster, by increasing the river length exponent from 0.33 to 1.0, the slope exponent changes from -0.50 to -0.03 . The minimum, maximum and average values of T_c in this cluster are about 0.10, 1.43 and 0.69 h, respectively. The CoV of this cluster is 72.3%, meaning that there is a high discrepancy between the CoV of this cluster and the other clusters.

- Cluster 3. This cluster is the largest, with about 41% of all the T_c equations falling in this cluster. Most of the equations in this cluster were developed for steep and

small mountainous catchments. Similar to the other clusters, the trend of the geomorphological parameter exponents plays an important role in the similarity between the T_c equations in this cluster. As shown in Figure 5(c), there is no unique trend between the river length and flow path slope exponents. By increasing the length exponent up to 0.55 there is an upward trend, while from 0.55 to 1 the trend between river length and flow path slope exponents reverses. Statistical analyses showed that the minimum, maximum and average values

of T_c in this cluster are about 2.14, 4.18 and 3.12 h, respectively.

- Cluster 4. This cluster is the smallest cluster, comprising only two equations, the Simas–Hawkins and Haktanir–Sezen formulas. One of the main reasons for this clustering is that, unlike all the other T_c equations, in the Simas–Hawkins formula, by increasing length variable the value of T_c decreases and vice versa. In addition, in this formula, the exponent of the length variable is larger than those of the equations in clusters 1–3, and this issue leads to a larger estimation of T_c .
- Cluster 5. This cluster is also small, containing only the Epsey, Sheridan and Flavell equations. Relative to the other clusters, there is a significant difference between the estimated and observed T_c values. Statistical analyses revealed that the minimum and maximum values of T_c in this cluster are about 25.27 and 38.62 h, respectively. The findings reveal that using formulas that depend on only one geomorphological parameter (e.g. river length (Sheridan) or catchment area (Flavell)) is not an appropriate approach for estimating T_c , especially in ungauged catchments. However, according to the T_c values of these formulas and the equations in cluster 4, it might be reasonable to say that clusters 4 and 5 are almost the same. These clusters were thus merged to form a single cluster, as shown in Table 6.

4. Conclusions

The limitations of several empirical/semi-empirical time of concentration (T_c) equations lead to much confusion in selection of the best formulas for estimating T_c . In this study, an efficient approach, based on salt dilution tracing, was used to estimate T_c values in the Meime catchment, Iran. In addition, 36 previously proposed T_c formulas were classified. From the data obtained on seven sub-watersheds in the Meime catchment, it is possible to conclude that the most efficient T_c formulas for this region are the Picking, Pickering, DNOS, California and Kirpich-Ten equations. T_c estimates made from different empirical or semi-empirical formulas are subject to significant error when applied to a single catchment. For all the sub-basins of the Meime catchment, with a mean T_c of 48.1 min and a range from 28.2–79.1 min, the maximum errors for the 36 T_c equations were found to vary between 2.6 and 132.8 min. It is obvious that errors in estimating T_c can significantly affect hydrological designs. The significant inaccuracies in the T_c equations may be due to different contributing factors. Firstly, the input variables needed for all the T_c formulas are different and, secondly, the empirical coefficients (constant or exponent coefficients) of all the T_c formulas differ because each was calibrated for a specific region with a limited range of input parameters that differ substantially from the values of other catchments.

Categorising the most similar equations revealed that there were five clusters with the highest similarity within the

members of each cluster. One of the most important factors that increases these similarities is the empirical coefficients of the T_c equations. In each cluster, the relationship between the exponents of the most important geomorphological parameters and the limitations of the T_c formulas were found to be different from those in other clusters. For instance, in some clusters, the relationship between the exponents of flow path slope and river length showed an upward trend, while a downward trend was observed in other clusters. This study also revealed that equations with the same development conditions mostly fell into a specific cluster. The findings of this study clearly show that salt experiments can be used as an appropriate approach for estimation of T_c values, especially in data-sparse catchments that are challenged with many data-related problems.

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