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Determination of Time of Concentration for Ungauged Arid Region Catchments

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Abstract An empirical approach that utilizes the catchment morphological parameters and hydrological characteristics has been developed to assess in the calculation of time of concentration in ungauged arid region catchments. The data incorporated in the developed method are easy to obtain from satellite images and by utilizing GIS techniques without the need for intensive fieldwork or relying on lengthy historical runoff records. Rainfall data can be obtained from raingauge records that distributed in the area. The developed method has been obtained empirically by correlating time of concentration with different effective catchment parameters non-linearly. The developed method has been tested against three well-known and widely used methods by utilizing linear correlation as a means for comparison; utilizing 61 rainfall-runoff events from 11 catchments in 3 countries located in different parts of the world; and showed superiority to these methods. Also, simulated time of concentration produced by applying the developed method has shown reasonable comparison when compared with the observed time of concentration.

Keywords Peak flow · Rainfall-runoff · SCS-CN · SCS-UH · Wadis · GIS

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الخلاصـة

تم - في هذه الدراسة - استحداث طريقة تجريبية تعتمد على المتغيرات الجيمورفولوجية والخصائص الهيدرولوجية لمستجمعات الأمطار في المناطق الجافة ، للمساعدة في حساب زمن التركيز لهذه المستجمعات التي لا تتوفر فيها أجهزة قياس. ويمكن استخلاص المعلومات المطلوبة لهذه الطريقة بسهولة من صور الأقمار الاصطناعية، وباستخدام تقنية نظم المعلومات الجغرافية - بدون الحاجة إلى عملٍ حقلي مكثف أو الاعتماد على تسجيلات السيول التاريخية بعيدة المدى.

كما يمكن الحصول على معلومات الأمطار المطلوبة من مسجلات الأمطار الموزعة في المنطقة أو حولها. ولقد تم الحصول على معادلة الارتباط التجريبية لهذه الطريقة باختبار الارتباط غير الخطي بين زمن التركيز وعدد من المتغيرات المؤثرة لمستجمعات الأمطار. كما تم اختبار الطريقة المستحدثة ضد ثلاث طرق مشهورة ومستخدمة بشكل واسع - بتطبيق الارتباط الخطي بين نتائج الطريقة المستحدثة مع كل منها على سبيل المقارنة - باستخدام 61 حادثة مطر وسيول مسجلة في 11 مستجمعاً للمطر توجد في ثلاث دول متفرقة في أماكن مختلفة من العالم ، ولقد بيّنت الطريقة المستحدثة تفوّقها على الطرق الأخرى.

1 Introduction

Determination of peak flow magnitude is a very essential issue in hydrology, which is required as the fundamental value in many hydrological applications such as hydraulic structure design and rainfall-runoff modeling calibration and validation. In arid region in particular where there is scarcity of runoff records and most catchments are ungauged, this issue becomes more critical [1,2]. In addition, owing to the deficiency of reliable rainfall and runoff gauge networks and due to spatial variation of the hydrological characteristics in arid region ungauged wadis quantitative assessment of runoff is not an easy task [3]. A number of approaches and techniques using physical, morphological, and statistical methods have been developed to determine the flood peak in arid regions by a number of investigators [4–8].

Where there are no or insufficient runoff gauges in the area, the problem becomes more pronounced and thus it is necessary to implement alternative techniques such as empirical formula that do not require recorded runoff data. Also, the limited hydrological investigations in arid region floods indicates that physically based approaches are not yet able to predict these features accurately with less calibration and simple empirical or semi-empirical formula may perform equally well or even better [9,10]. A number of empirical formula and approaches has been developed over the years to deal with this topic [11]. These methods usually relate the peak discharge with empirical parameters related somehow to hydrological and morphological variables. However, one of the most widely used methods to determine flood peak in arid regions is based on the determination of unit hydrograph (UH) of the catchment which is mainly reliant on the accurate determination of time of concentration as the prime parameter such as in the Snyder synthetic unit hydrograph [12] and in Soil Conservation Service unit hydrograph method (SCS-UH) [13].

In arid regions' ungauged catchments, due to lack of reliable and adequate data, it is most difficult to find the appropriate time of concentration for a catchment by model calibration. Also, time of concentration is dependent on both morphological as well as hydrological conditions of the catchment. Morphological parameters of a catchment are static but hydrological parameters such as rainfall characteristics, antecedent moisture condition, and runoff coefficient are dynamic. This complicates matter and makes the determination of time of concentration even more difficult in these areas.

Usually empirical methods such as Kirpich method [14], Aron and Egborge method [15], Federal Aviation Administration (FAA) [16], and SCS lag equation [13] are utilized. Nevertheless, these methods have been developed and tested at specific areas and there is no evidence of superiority of one method over the others when application on different part of the world is considered. Some of these formulas utilize morphological data only while others use a mixture of morphological and hydrological data. Recent development in remote sensing, digital elevation models (DEMs) and GIS technology alleviates and improves the accuracy of the determination of catchment morphology and channel geometry, which can be utilized for applying simple empirical methods for the determination of time of concentration with great confidence.

In this paper, an empirical approach that incorporates catchment morphological and hydrological parameters has been developed for the determination of time of concentration in arid region ungauged catchments. Data for this approach can be obtained from satellite images, air photos and/or DEMs and measured rainfall records for particular events. The data incorporated in the developed method are easy to obtain from satellite images which can be analysed by utilizing GIS techniques without the need for intensive fieldwork. The suggested method has been developed by correlating 61 historical rainfall-runoff events in 11 catchments from 3 different countries in different parts of the world. The developed method has been tested against three well-known methods in this field and showed its superiority in terms of goodness of fit with the observed time of concentration of these events.

2 Methodology

The developed method is based on incorporating the most important catchment morphological and hydrological factors to account for both static and dynamic characteristics to provide a realistic determination for time of concentration. Significance of a number of morphological and hydrological parameters has been tested to produce reasonable time of concentration for all the simulated rainfall-runoff events. The tested factors include catchment area, curve number, catchment average slope, main channel length, catchment maximum potential storage, total rainfall and effective rainfall depths, and runoff coefficient. However, due to the dependency of some of these factors on one another some of these parameters were found irrelevant for the determination of time of concentration and including them does not add any value to the developed equation. However, it was found that the most significant catchment morphological parameters, which are included in this approach, are average catchment slope and main channel length while the most significant hydrological parameters include only event storage depth (depth of rainfall loss for a certain event). Depth of rainfall loss (d, mm) has been chosen because it reflects the most important hydrological parameters as it is strongly related and represents total rainfall depth, effective rainfall and hence runoff coefficient and curve number of that particular event. This can be represented as the difference between total rainfall depth (P, mm) and the effective rainfall depth (runoff depth) (P_e; mm) as shown in Eq. 1:

$$d = P - P_e \quad \text{for } P > P_e. \tag{1}$$

This equation is not applicable for a completely impervious catchment which is not the case in natural catchments. Effective rainfall depth (P_e) can be calculated from the maximum storage of the catchment (S, mm) and total rainfall depth (P, mm) as shown in the following equation:

$$P_e = \frac{(P - 0.2S)^2}{P + 0.8S}. \tag{2}$$

Table 1 Catchment and rainfall characteristics for the utilized rainfall-runoff events

Country	Catchment	Date	Area (km^2)	L (m)	Y (m/m)	P (mm)	P_e (mm)	d (mm)
Saudi Arabia	Thara	25-11-84	290	23,000	0.201	27.59	1.003	26.587
		5-9-85	290	23,000	0.201	9.83	0.170	9.66
		18-9-85	290	23,000	0.201	10.8	0.275	10.525
		19-12-85	290	23,000	0.201	9.49	0.245	9.245
		2-3-86	290	23,000	0.201	37.51	0.760	36.75
		30-7-86	290	23,000	0.201	51.23	2.604	48.626
		7-8-87	290	23,000	0.201	16.77	1.513	15.257
		9-8-87	290	23,000	0.201	16.17	1.048	15.122
	Al-Hamid	15-5-84	170	22,137	0.075	10.27	1.715	8.555
		25-1-85	170	22,137	0.075	21.13	2.008	19.122
		5-4-85	170	22,137	0.075	40.13	2.886	37.244
		23-4-85	170	22,137	0.075	18.4	0.239	18.161
		1-5-85	170	22,137	0.075	19.46	0.914	18.546
		2-4-87	170	22,137	0.075	12.47	1.328	11.142
		2-8-87	170	22,137	0.075	11.0	0.517	10.483
	Al-Jawf	20-9-84	320	17,000	0.269	10.24	0.279	9.961
		5-4-85	320	17,000	0.269	38.76	1.794	36.966
		23-4-85	320	17,000	0.269	36.02	0.847	35.173
		1-5-85	320	17,000	0.269	13.3	1.160	12.14
		5-5-85	320	17,000	0.269	26.76	0.342	26.418
		12-5-85	320	17,000	0.269	14.08	0.442	13.638
		17-5-85	320	17,000	0.269	16.38	0.732	15.648
		22-5-85	320	17,000	0.269	26.98	0.693	26.287
		30-7-86	320	17,000	0.269	17.72	5.530	12.19
		28-9-86	320	17,000	0.269	18.70	1.389	17.311
		1-3-87	320	17,000	0.269	48.26	2.977	45.283
	Goase	29-9-09	67.5	18,740	0.053	80.0	58.49	21.51
Oman	Ahin	22-1-96	734	37,500	0.03	28.5	4.6	23.9
		24-1-96	734	37,500	0.03	32.5	10	22.5
		11-3-96	734	37,500	0.03	20.7	5.7	15
		27-06-96	734	37,500	0.03	4.4	0.5	3.9
		7-8-96	734	37,500	0.03	9.2	1.3	7.9
		25-1-97	734	37,500	0.03	34.6	2.7	31.9
		8-8-97	734	37,500	0.03	10	1.1	8.9
		13-9-97	734	37,500	0.03	5.8	0.7	5.1
		11-10-97	734	37,500	0.03	4.1	0.7	3.4
		29-10-97	734	37,500	0.03	6	1.4	4.6
		2-11-97	734	37,500	0.03	5.7	0.8	4.9
		27-1-98	734	37,500	0.03	22.5	2	20.5
		13-6-98	734	37,500	0.03	5.1	0.1	5
		20-7-98	734	37,500	0.03	10.3	1.3	9
		8-8-98	734	37,500	0.03	4.9	0.4	4.5
		6-9-98	734	37,500	0.03	5	0.4	4.6
		2-3-99	734	37,500	0.03	14.4	3	11.4
USA	Monument Draw	4-6-65	21.3	5,210	0.136	21.1	1.22	19.88
		7-9-73	21.3	5,210	0.136	14.22	3	11.22
		10-9-73	21.3	5,210	0.136	30.5	4.11	26.39
	West Fork Upper	12-6-67	1.79	1,508	0.045	26.4	7.4	19
		10-6-69	1.79	1,508	0.045	40.6	23.52	17.08
	West Fork Lower	23-6-67	4.8	2,471	0.067	19.05	2.11	16.94
		10-6-69	4.8	2,471	0.067	32.5	12.9	19.6
		5-6-72	4.8	2,471	0.067	59.4	30.9	28.5
	Badwater	14-6-67	15.2	4,397	0.091	23.11	2.08	21.03
		16-7-68	15.2	4,397	0.091	13.00	1.73	11.27
		10-6-69	15.2	4,397	0.091	15.24	1.09	14.15
	North Prong	21-5-70	9.8	3,527	0.146	6.86	2.34	4.52
		28-5-71	9.8	3,527	0.146	14.22	1.73	12.49
	Third Sand	26-9-66	28	5,969	0.115	9.14	0.74	8.4
		9-9-67	28	5,969	0.115	13.72	1.32	12.4
		8-6-68	28	5,969	0.115	12.19	1.91	10.28
		8-7-68	28	5,969	0.115	23.11	4.32	18.79

Table 1 continued

Country	Catchment	Date	Area (km^2)	L (m)	Y (m/m)	P (mm)	P_e (mm)	d (mm)
		Min	1.79	1,508	0.03	4.10	0.10	3.40
		Max	734	37,500	0.27	80.00	58.49	48.63
		Average	325.16	20,530.80	0.12	20.61	3.79	16.83
		SD	280.51	12,725.38	0.09	14.71	8.77	10.41

Catchment maximum storage (S, mm) can be calculated based on the curve number (CN) value if this is available. Once the curve number value is obtained, catchment maximum storage can be calculated from the following equation:

$$S = \frac{25{,}400}{\mathrm{CN}} - 254. \tag{3}$$

The developed time of concentration equation was obtained in this work by applying different power formula and correlating the results with the observed time of concentration from the recorded 61 rainfall-runoff events at 11 catchments from 3 different countries. Data for these events, as shown in Table 1 were collected from the Ministry of Water and Electricity and [17]; for Saudi Arabia, from [10]; for Oman, and from [18]; for USA.

The utilized catchments cover an area that ranges between 2 and 730 km^2. The calibrated time of concentration has been obtained by applying the SCS curve number method for rainfall loss calculation and SCS dimensionless unit hydrograph (SCS-UH) for hydrograph generation as in [17]. In this approach, data from the observed rainfall-runoff events are utilized to obtain the actual time of concentration. Time of concentration is the only unknown for the recorded historical events. This parameter (actual time of concentration for each event) has been determined by calibration to fit the actual peak discharge and runoff volume with the recorded rainfall and catchment characteristics by using the SCS-CN methods and SCS dimensionless UH. The determined time of concentration for each event is considered as the observed time of concentration in this paper which is shown in Table 2 for each simulated event.

The developed nonlinear equation (shown as Eq. 4) was originated by finding the best fit for the linear relationship between calculated and observed time of concentration:

$$T_c = 0.033 d^{0.1} L^{0.2} Y^{-0.65} \quad \text{for } Y \text{ and } d > 0, \tag{4}$$

where T_c is the time of concentration; hours, L is the main channel length; m, Y is the average catchment slope; m/m and d is as in Eq. 1 above. Calculated time of concentration values by the developed equation (Eq. 4) for all events is shown in Table 2. These values were plotted against the observed time of concentration values in Fig. 1 and coefficient of determination has been calculated as 0.57. Although, this value may look low but comparing it with values of other widely applicable methods shows the superiority of this method over the others. Testing this method against other methods is explained in detail in the next section.

3 Method Verification and Results Discussion

The developed equation (Eq. 4) was verified by testing it against three well-known and widely used methods for the determination of time of concentration. These methods are Kirpich [14], Federal Aviation Administration [16], and SCS lag time [13] as shown in Eqs. 5, 6, and 7, respectively:

$$T_c = 0.00013 L^{0.77} Y^{-0.385} \tag{5}$$

$$T_c = 0.03(1.1 - C) L^{0.5} B^{-0.333} \tag{6}$$

$$T_c = 0.000878 L^{0.8} B^{-0.5} (S+1)^{0.7}. \tag{7}$$

In Eqs. 5, 6, and 7 L is the main channel length (ft), C is the calculated runoff coefficient for a particular event, Y is the catchment average slope (ft/ft), and B is the catchment average slope in percentage such that:

$$B = 100Y \tag{8}$$

and S is the catchment maximum potential storage (ft). Runoff coefficient can be calculated as the ratio between effective rainfall depth and total rainfall depth as shown in the following equation:

$$C = \frac{P_e}{P}. \tag{9}$$

Calculated values of time of concentration by the developed method (Eq. 4) and by the three methods in Eq. 5, 6, and 7 are shown in Table 2. The calculated time of concentration values by the three tested methods have been correlated individually with the observed time of concentration as shown in Figs. 2, 3, and 4, respectively.

It can be noticed from Figs. 1, 2, 3, and 4 that coefficient of determinations are 0.57, 0.52, 0.44, and 0.42 for the developed method, Kirpich, FAA, and SCS methods, respectively. This shows that although the coefficient of determination is low for the developed method, yet it has a significant improvement over the other well-known and widely applied methods in this field. By comparing the

Table 2 Calculated time of concentration from the developed methods and three other methods versus the observed time of concentration for the utilized rainfall-runoff events

Country	Catchment	Date	Observed T_c (h)	Developed T_c (h)	Kirpich T_c (h)	FAA T_c (h)	SCS T_c (h)
Saudi Arabia	Thara	25-11-84	0.93	0.979	1.374	3.227	4.461
		5-9-85	0.52	0.884	1.374	3.285	2.907
		18-9-85	0.73	0.892	1.374	3.260	2.940
		19-12-85	0.9	0.881	1.374	3.259	2.787
		2-3-86	1.16	1.011	1.374	3.276	5.674
		30-7-86	0.79	1.040	1.374	3.183	6.052
		7-8-87	0.97	0.926	1.374	3.064	3.050
		9-8-87	1.55	0.925	1.374	3.141	3.161
	Al-Hamid	15-5-84	0.94	1.646	1.950	3.856	3.639
		25-1-85	0.6	1.783	1.950	4.154	5.321
		5-4-85	1.34	1.906	1.950	4.249	7.827
		23-4-85	1.25	1.774	1.950	4.493	6.300
		1-5-85	1.24	1.778	1.950	4.352	5.721
		2-4-87	0.72	1.690	1.950	4.106	4.184
		2-8-87	0.78	1.679	1.950	4.352	4.442
	Al-Jawf	20-9-84	0.78	0.691	0.973	2.539	1.943
		5-4-85	0.65	0.788	0.973	2.494	3.540
		23-4-85	0.55	0.784	0.973	2.548	3.703
		1-5-85	0.66	0.705	0.973	2.397	1.892
		5-5-85	0.95	0.762	0.973	2.574	3.300
		12-5-85	0.42	0.713	0.973	2.530	2.198
		17-5-85	1.15	0.723	0.973	2.498	2.267
		22-5-85	0.66	0.761	0.973	2.543	3.114
		30-7-86	0.54	0.705	0.973	1.865	1.599
		28-9-86	0.8	0.730	0.973	2.428	2.244
		1-3-87	0.76	0.804	0.973	2.458	3.831
	Goase	29-9-09	1.58	2.187	1.961	1.575	4.001
Oman	Ahin	22-1-96	1.7	3.676	4.165	6.851	13.087
		24-1-96	2.8	3.654	4.165	5.783	11.293
		11-3-96	4.3	3.509	4.165	6.019	9.839
		27-06-96	3.7	3.067	4.165	7.199	7.506
		7-8-96	4.2	3.291	4.165	6.997	8.732
		25-1-97	4.3	3.784	4.165	7.459	17.120
		8-8-97	1.9	3.330	4.165	7.226	9.305
		13-9-97	2.05	3.150	4.165	7.148	7.915
		11-10-97	3.1	3.025	4.165	6.783	7.137
		29-10-97	3.3	3.118	4.165	6.326	7.342
		2-11-97	2.8	3.137	4.165	7.004	7.751
		27-1-98	1.9	3.620	4.165	7.380	13.393
		13-6-98	2.3	3.144	4.165	7.886	8.773
		20-7-98	2.3	3.334	4.165	7.108	9.182
		8-8-98	1.55	3.111	4.165	7.433	7.874
		6-9-98	3.3	3.118	4.165	7.445	7.956
		2-3-99	1.43	3.414	4.165	6.508	9.346
USA	Monument Draw	4-6-65	1.5	0.911	0.509	1.714	1.348
		7-9-73	3	0.860	0.509	1.462	0.897
		10-9-73	2.1	0.937	0.509	1.587	1.374
	West Fork Upper	12-6-67	0.8	1.452	0.300	1.048	0.643
		10-6-69	1.3	1.436	0.300	0.666	0.563
	West Fork Lower	23-6-67	1.5	1.223	0.376	1.418	0.903
		10-6-69	1.3	1.241	0.376	1.008	0.772
		5-6-72	1	1.288	0.376	0.831	0.842
	Badwater	14-6-67	0.55	1.149	0.522	1.744	1.393
		16-7-68	0.6	1.080	0.522	1.670	1.021
		10-6-69	0.6	1.105	0.522	1.776	0.742
	North Prong	21-5-70	0.9	0.693	0.367	1.003	0.538
		28-5-71	0.8	0.768	0.367	1.293	0.538
	Third Sand	26-9-66	0.7	0.957	0.603	1.897	0.878
		9-9-67	0.95	0.995	0.603	1.869	0.878

Table 2 continued

Country	Catchment	Date	Observed T_c (h)	Developed T_c (h)	Kirpich T_c (h)	FAA T_c (h)	SCS T_c (h)
		8-6-68	1.1	0.977	0.603	1.756	0.878
		8-7-68	1.45	1.038	0.603	1.700	0.878
		Min	0.42	0.69	0.30	0.67	0.54
		Max	4.30	3.78	4.16	7.89	17.12
		Average	1.49	1.72	1.90	3.72	4.60
		SD	1.02	1.07	1.49	2.25	3.78

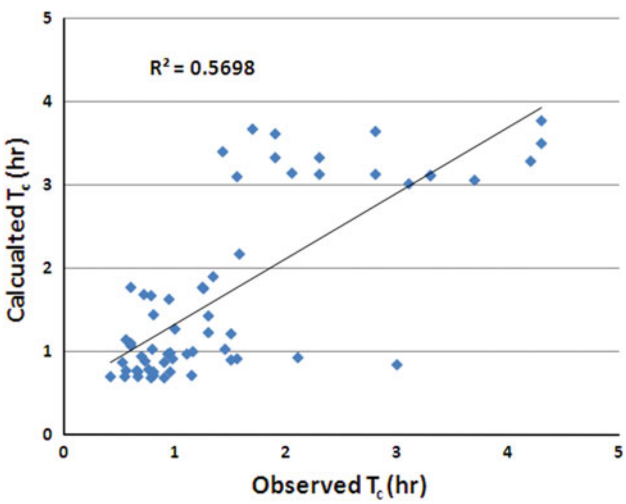

Fig. 1 Calculated time of concentration values by the developed method versus observed time of concentration

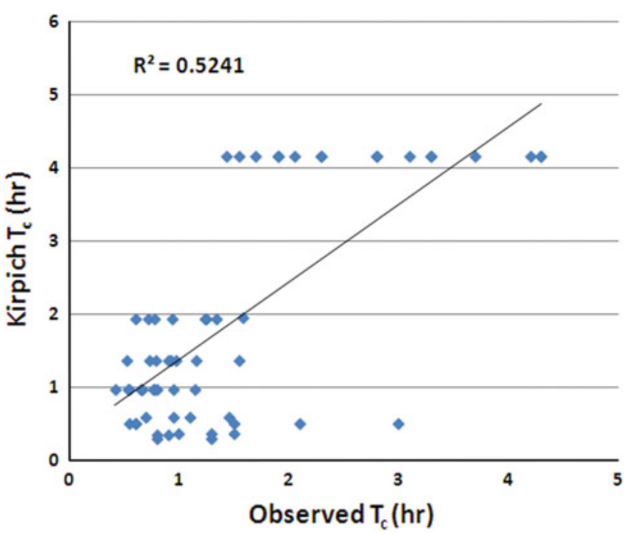

Fig. 2 Calculated time of concentration values by the Kirpich method versus observed time of concentration

averages and standard deviations between the developed method and the observed time of concentration and the other three methods in Table 2; a considerable and significant improvement in the prediction of time of concentration by the new method can be noticed.

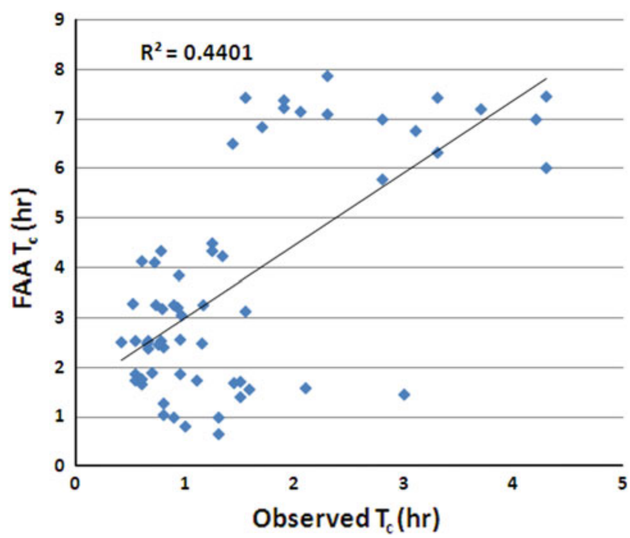

Fig. 3 Calculated time of concentration values by FAA method versus observed time of concentration

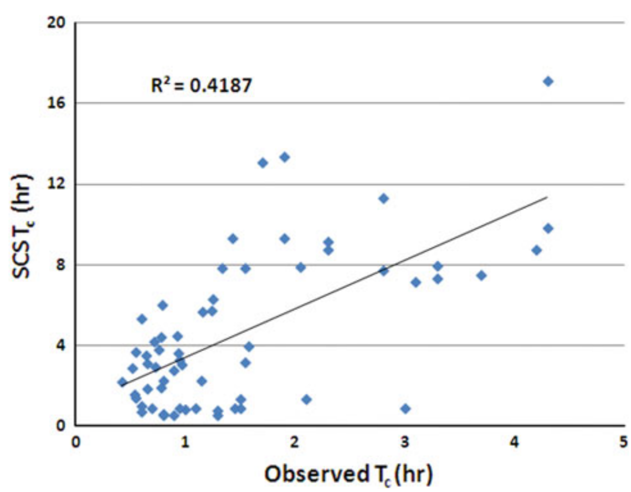

Fig. 4 Calculated time of concentration values by SCS method versus observed time of concentration

4 Conclusion

An empirical approach for the determination of peak discharge in arid region ungauged wadis has been developed in this paper based on catchment morphological and hydrological parameters. Due to shortage of existing discharge gauging stations and records in arid regions, it has been taken into consideration that the utilized data in the developed method should be independent of lengthy historical runoff records in these areas. The data incorporated should also be easy to obtain from satellite images and analysed by utilizing GIS techniques without the need for intensive field visits.

The developed method has been obtained by utilizing 61 rainfall-runoff events from 3 different countries in different parts in the world. Morphological data included in the developed approach are catchment average slope and main channel length. Utilized catchment average slope ranges from 0.03 to 0.27, and main channel length ranges from 1,500 to 37,500 m. Hydrological data required for this method is the catchment effective rainfall depth from the rainfall event which ranges between 0.1 and 49 mm and catchment curve number value. These parameters reflect implicitly total rainfall depth, effective rainfall depth and antecedent moisture condition as represented by runoff coefficient and curve number. The morphological parameters in this approach can be determined easily from satellite images and GIS technique while hydrological parameters can be determined from raingauge data in the area. Catchment geomorphological data can be obtained from satellite images which can be converted into digital elevation models (DEMs) and analysed by GIS software include curve number (CN), main channel length (L) and average catchment slope (Y).

By correlating the developed method results with the observed time of concentration and by comparing the results with three other widely used methods, it was found that the coefficient of determination for the developed method is the highest (0.57) among all other methods. Also, in terms of minimum, maximum, average, and standard deviation values the developed method produces the closest values to the observed ones (Table 2). The second closest method is Kirpich with 0.52 coefficient of determination, and 0.44 and 0.42 for the FAA and SCS methods, respectively. Although Kirpich method has produced the second closest fit to the observed time of concentration it only relates catchment morphological parameters and does not take hydrological parameters into account. It was also observed that both FAA and SCS overestimate the time of concentration for large catchments (area is $>30\,\text{km}^2$) and underestimate it for small catchments. It can be seen that FAA and SCS are more suitable for small catchments (area is $<30\,\text{km}^2$) than for the large catchments. These method, however, may perform better when large catchments are divided into smaller sub-catchments for which time of concentration is calculated for each sub-basin individually and then added up to calculate time of concentration for the whole catchment. The developed method has shown to be superior to other methods especially for the determination of time of concentration for larger catchments with catchment area more than $30\,\text{km}^2$.

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