Iranian Journal of Science and Technology, Transactions of Civil Engineering (2024) 48:467–482
https://doi.org/10.1007/s40996-023-01286-5

RESEARCH PAPER

Estimation of Regional Design Runoff Coefficient in the Rational Method

Touraj Sabzevari[1] · **Ali Torabi Haghighi**[2] · **Zahra Ghadampour**[1] · **Andrea Petroselli**[3] · **Hossein Namazi**[1]

Received: 17 September 2022 / Accepted: 31 October 2023 / Published online: 8 December 2023

Abstract

The rational method is commonly used to estimate the design floods in catchments. An accurate estimation of surface runoff and the related design floods depends on the runoff coefficient precision, which is associated with several factors such as rainfall and soil infiltration rate. In the rational method, the design runoff coefficient (C_T) is defined as a function of land use, soil type, slope, and return period. A technique is proposed here to compute C_T based on the regional analysis of daily rainfall and soil conservation service curve number (SCS-CN) infiltration parameters. Daily rainfall data of 83 rain gauge stations in Sothern Iran (Fars province) were used to calculate the C_T for various land uses and return periods for four rainfall rate categories. Equations were introduced to determine C_T as a function of the return period and curve number in different catchments of the world. The regression correlation coefficient was calculated to be above 0.99 for the suggested equations. Based on the suggested method, for design purpose, the CN standard tables in the SCS method were converted into C_T tables for the return period 10–500 years in Fars province, Iran.

Keywords Regional runoff coefficient · Rational method · Return period · Fars province

1 Introduction

The rational method is widely used to estimate the maximum runoff of small catchments (Schaake 1967; Guo 2001; Akan 2002; Young et al. 2009; Sabzevari 2010, 2017; Dhakal et al. 2010; Grimaldi and Petroselli 2015; Chin 2019; Baiamonte 2020; Ardekani et al. 2021; Lapides et al. 2021; Machado et al. 2022). This technique is widely used to calculate the design flood of hydraulic structures, spatially in the design of drainage systems in urban areas (Baiamonte 2020; Chin 2017; Froehlich 2016; Cleveland et al. 2011; Al-Amri et al. 2022, Młyński et al. 2020). The maximum runoff of the catchment is determined as follows (Kuichling 1889):

$$Q_T = 0.278 \times C_{T\times} I_T \times A \quad (1)$$

where Q_T is the design discharge (m^3s^{-1}), C_T is the design runoff coefficient (C_T), A is basin area (Km^2), and I_T is the design rainfall intensity (mm/h). The runoff coefficient (RC) plays a crucial role in the rational formula (Eq. 1). It is defined based on soil type, land use, and slope of the basin (Longobardi et al. 2003; Sriwongsitanon and Taesombat 2011; Zhang et al. 2014), is accessible in tabular form in many hydrologic textbooks Chow (1962), and it determines the amount of excess rainfall.

Most of the available C_T tables were extracted based on regional information from specific catchments and are unusable for other regions and catchments. Therefore, it is important to have a regional approach to estimate C_T.

RC in the rational method is commonly adjusted by return period (Jens 1979; Bernard 1938; Dhakal et al. 2013). Based on the return period, the value of RC can be increased to calculate the C_T (Ken-Bohuslav 2004). Furthermore, the RC is used to estimate plain's water balance (Fariborzi et al. 2019; Giordano et al. 2010; Peng et al. 2019; Lu et al. 2018), to calculate the concentration time (Li and Chibber 2008), and directly in rainfall-runoff models. For example, in the Soil Conservation Service (SCS) model, excess rainfall can be

✉ Touraj Sabzevari
tooraj.sabzevari@yahoo.com

[1] Department of Civil Engineering, Islamic Azad University, Estahban Branch, Fars, Iran

[2] Water, Energy and Environmental Engineering Research Unit, University of Oulu, Oulu, Finland

[3] Department of Economics, Engineering, Society and Business Organization (DEIM), Tuscia University, Via S. Camillo de Lellis Snc, 01100 Viterbo, VT, Italy

calculated from different infiltration methods (e.g., Green-Ampt, Soil Conservation Service Curve Number—SCS-CN, or Horton). In SCS-CN models, infiltration rate can be estimated based on Curve Number (CN) which is correlated with RC parameters (Kim and Shin 2018; Mishra and Singh 2013). Furthermore, the infiltration process depends on the slope, topography, initial moisture, rainfall, and land cover (Dunne et al. 1991; Huang et al. 2013; Dunkerley 2012; Pishvaei et al. 2020). In addition, RC varies from one event to another because of variation in rainfall, infiltration, and soil moisture conditions, thus it is important to consider these factors in determining the RC.

Recent studies confirm the relationship between return period and runoff coefficient. (Froehlich 2016; Hotchkiss and Provaznik 1995; Titmarsh et al. 1995; Young et al. 2009; Dhakal et al. 2013; Dhakal et al. 2012). For example, Dhakal et al. (2010) found that the rational runoff coefficients increase with the return period and the rate of increase is much larger than what typically recommended in design manuals. Froehlich (2016) compared runoff coefficient adjustment factors and found that the return period adjustment factors illustrated a large difference, caused by the wide variability of parameters that influence the catchment runoff (such as precipitation, soils, and land-surface cover) within a region as vast as Texas.

However, Chin (2017) showed that Froehlich (2016) equated the incremental rainfall excess within each time interval to the incremental runoff predicted by the Natural Resources Conservation Service (NRCS 1972) Curve Number (CN) model when calculating the runoff hydrograph and this could have led to physically unrealistic results (e.g., Morel-Seytoux and Verdin 1981; Chin 2013).

Based on SCS-CN infiltration relations, equations are presented in this research to calculate C_T as a function of land use (CN) and design return period.

The proposed method is compared and evaluated with the methods and standards presented in previous research. One of the important objectives of this study is to convert the standard CN tables into C_T calculated and presented in tabular form for 4 different climates in Fars province, Iran.

2 Methodology

In this part, we first explain the fundamental concept of the rainfall-runoff process, then present our approach for modifying the runoff coefficient for different return periods.

3 Runoff Coefficient Concept

Runoff coefficient is the percentage of rainfall that is converted to runoff according to the following formula:

$$RC = \frac{R}{P} \tag{2}$$

where P and R are the rainfall and runoff depths, and RC is the runoff coefficient. In a gauged basin with available observed runoff hydrograph, the runoff volume equals the area below the hydrograph curve. The depth of runoff ($R = V/A$) is obtained by dividing the volume of runoff (V) by the area of basin (A). Furthermore, based on the continuity equation, the amount of rainfall (P) is equal to the sum of infiltration depth (F) and runoff depth (R). Therefore, the runoff depth can be calculated by subtracting the infiltration from the rainfall depth ($R = P - F$). Runoff rate changes temporally and spatially across the basin due to the spatial–temporal variation affecting factors on the infiltration process, e.g., soil permeability and soil moisture. This spatial–temporal variation affecting the parameter of infiltration is a source of uncertainty and influences the accurate estimation of the runoff coefficient.

4 Design Rainfall

The design rainfall intensity in the rational formula (Eq. 1) can be obtained by regional Intensity–Duration–Frequency (IDF) curves (Madsen et al. 2009; Soltani et al. 2017; Courty et al. 2019) as follows:

$$I_T^{t_d} = \frac{aT^b}{t_d + f} \tag{3}$$

where t_d is the rainfall duration, T is the return period, a, b and f are regional coefficients. Based on this, the following equation can be applied to estimate the design rainfall in Iran (Ghahraman and Abkhezr 2004):

$$P_T^{t_d} = [0.2471 ln(T - 0.6)(0.37 + 0.618 {t_d}^{0.45}](P_2^{24})^{1.14}(e)^{0.291} \tag{4}$$

where $P_T^{t_d}$ is the design rainfall (mm), t_d is the rainfall duration (minutes), P_2^{24} is the 24-h maximum rainfall with a 2-year return period. Rainfall duration is usually considered equal to the time of concentration of the basin.

5 Regional Design Runoff Coefficient

To estimate the maximum runoff by rational formula, the design runoff coefficient (C_T) is considered higher than the RC of the basin. Here we suggested two different approaches for calculating C_T for ungauged and gauged basins.

5.1 Ungauged Basins

In ungauged basins, only rainfall data are available. Based on the maximum 24-h rainfall (maximum daily rainfall) the rainfall with different return periods (P_T) will be estimated (Apollonio et al. 2018; Hajani and Rahman 2018; Merkel et al. 2017). The best-fitted probability distribution of the maximum 24-h rainfall (e.g., Normal, Lognormal, Gumbel, Pearson type III, Log Pearson type III) can be used to determine the design rainfall. Then, based on the best-fitted probability distribution, the design rainfall can be estimated as (Chow et al. 1962):

$$P_T = \overline{P} + K_T S \tag{5}$$

where $\overline{P}$ and S are the mean and standard deviation of maximum 24-h rainfall, and K_T is the frequency factor which is calculated based on the best-fitted probability distribution (Chow et al. 1962); for example, for Gumbel distribution, it can be calculated as:

$$K_T = -\frac{\sqrt{6}}{\Pi}\left[0.5772 + ln\left(ln\left(\frac{T}{T-1}\right)\right)\right] \tag{6}$$

Equation 6 is suitable where the rainfall data are high, and if the amount of data are low, the Gumbel distribution frequency factor tables should be used. In any case, the equations of the best statistical distribution should be used by the rainfall data of the catchments. In this study, the Gumbel distribution was the best. Then the runoff depth can be estimated based on the SCS-CN method (Menberu et al. 2015):

$$R = \frac{(P - 0.2SR)^2}{P + 0.8SR} \tag{7}$$

where R and P are the runoff, and rainfall depth (mm) and SR is the maximum potential soil retention (mm), calculated as in the following:

$$SR = \left(\frac{25400}{CN} - 254\right) \tag{8}$$

where CN is the curve number parameter that is defined based on the land use and soil type (Table 1).

Substituting value R (Eq. 7) in Eq. 2, we can estimate the runoff coefficient as follows:

Table 1 CN values for various land use and soil hydrological groups (Chow et al. 1962)

Land use description		Hydrologic soil group			
		A	*B*	*C*	*D*
Cultivated land: without conservation treatment		72	81	88	91
With conservation treatment		62	71	78	81
Pasture or range land: poor condition		68	79	86	89
Good condition		39	61	74	80
Meadow: good condition		30	58	71	78
Wood or forest land: thin stand, poor cover, no mulch		45	66	77	83
Good cover		25	55	70	77
Open spaces, lawns, parks, golf courses, cemeteries, etc. good condition: grass cover on 75% or more of the area		39	61	74	80
Fair condition: grass cover on 50% to 75% of the area		49	69	79	84
Commercial or business areas (85% impervious)		89	92	94	94
Industrial districts (72% impervious)		81	88	91	93
Residential:					
Average lot size	Average % impervious				
1/8 acre or less	65	77	85	90	92
1/4 acre	38	61	75	83	87
1/3 acre	30	57	72	81	86
1/2 acre	25	54	70	80	85
1 acre	20	51	68	79	84
Paved parking lot, roofs, driveways, etc.		98	98	98	98
Street and roads:					
Paved with curbs and storm sewers		98	98	98	98
Gravel		76	85	89	91
Dirt		72	82	87	89

$$C_T = \frac{\left(P_T - 0.2SR\right)^2}{P_T\left(P_T + 0.8SR\right)} \quad (9)$$

The by substituting the calculated design rainfall (Eq. 5) in Eq. 9 the design runoff coefficient (C_T) can be estimated as follows:

$$C_T = \frac{\left(\bar{P} + K_T s - 0.2SR\right)^2}{\left(\bar{P} + K_T s\right)\left(\bar{P} + K_T s + 0.8SR\right)} \quad (10)$$

Most RC tables provided in ASCE and WPCF (1960) are valid for return periods of less than 10 years. For higher return periods, the design rainfall intensity increases and the infiltration decreases abruptly and the runoff coefficient increases. In this situation, the design runoff coefficient should be increased for the return period of more than 10 years (Dhakal et al. 2013).

In some references (e.g., Rossmiller 1980; Chow et al. 1962), tables have been provided to increase the runoff coefficient for different return periods (e.g., Table 2), but these tables have been calibrated for a specific basin in the world and are not valid for all basins with different climates.

Equation 10 shows that the design runoff coefficient is a function of the design rainfall with different return periods and the curve number as the infiltration parameter. Based on the best regional statistical distribution, you can compute design rainfall.

Equation 10 can better consider rainfall and soil infiltration conditions regionally.

5.2 Gauged Basins

In the gauged basin (basin has recorded stream discharge and flood data), the best-fitted probability distribution of

Table 2 Runoff coefficient for use in the rational method (Rossmiller 1980; Chow et al. 1962)

Character of surface	*a*, *R*	Return Period (years)						
		2	5	10	25	50	100	500
Developed								
Asphaltic	0.05, 0.97	0.73	0.77	0.81	0.86	0.90	0.95	1.00
Concrete/roof	0.05, 0.96	0.75	0.80	0.83	0.88	0.92	0.97	1.00
	Grass areas (lawns, parks, etc.)							
	Poor condition (grass cover less than 50% of area)							
Flat, 0–2%	0.09, 0.93	0.32	0.34	0.37	0.40	0.44	0.47	0.58
Average, 2–7%	0.08, 0.97	0.37	0.40	0.43	0.46	0.49	0.53	0.61
Steep, over 7%	0.07, 0.97	0.40	0.43	0.45	0.49	0.52	0.55	0.62
	Fair condition (grass cover less on 50% to 75% of area)							
Flat, 0–2%	0.11, 0.95	0.25	0.28	0.30	0.34	0.37	0.41	0.53
Average, 2–7%	0.09, 0.96	0.33	0.36	0.38	0.42	0.45	0.49	0.58
Steep, over 7%	0.08, 0.96	0.37	0.40	0.42	0.46	0.49	0.53	0.60
	Good condition (grass cover larger than 75% of area)							
Flat, 0–2%	0.12, 0.92	0.21	0.23	0.25	0.29	0.32	0.36	0.49
Average, 2–7%	0.10, 0.97	0.29	0.32	0.35	0.39	0.42	0.46	0.56
Steep, over 7%	0.08, 0.97	0.34	0.37	0.40	0.44	0.47	0.51	0.58
	Undeveloped							
	Cultivated land							
Flat, 0–2%	0.09, 0.95	0.31	0.34	0.36	0.40	0.43	0.47	0.57
Average, 2–7%	0.08, 0.97	0.35	0.38	0.41	0.44	0.48	0.51	0.60
Steep, over 7%	0.07, 0.97	0.39	0.42	0.44	0.48	0.51	0.54	0.61
	Pasture/range							
Flat, 0–2%	0.11, 0.95	0.25	0.28	0.30	0.34	0.37	0.41	0.53
Average, 2–7%	0.09, 0.96	0.33	0.36	0.38	0.42	0.45	0.49	0.58
Steep, over 7%	0.08, 0.96	0.37	0.40	0.42	0.46	0.49	0.53	0.60
	Forest/woodlands							
Flat, 0–2%	0.12, 0.98	0.22	0.25	0.28	0.31	0.35	0.39	0.48
Average, 2–7%	0.09, 0.90	0.31	0.34	0.31	0.40	0.43	0.47	0.56
Steep, over 7%	0.08, 0.98	0.35	0.39	0.42	0.45	0.48	0.52	0.58

the maximum of maximum 24-daily flow will be used to determine design flood for different return periods as follows:

$$Q_T = \bar{Q} + K_T S_Q \tag{11}$$

where Q_T is design flood for return period T, Q and S_T are mean and standard deviation of the maximum flow and K_T is frequency factor which is calculated based on the best-fitted probability distribution (Chow et al. 1962); for example the K_T for Gumbel distribution flow is shown in Eq. 6.

By substituting the value of Q_T in Eq. 1 the C_T can be calculated as (Pilgrim and Cordery 1993):

$$C_T = \frac{\bar{Q} + K_T S_Q}{0.278 I_T \times A} \tag{12}$$

6 Relationship Between *CT* and Return Period

Bernard (1938) presented the following relation for C_T:

$$C_T = C_{\max} \times (\frac{T}{100})^a \tag{13}$$

where $C_{\max}$ is the value of design runoff coefficient for a return period of 100 years, T is return period and a is coefficient which ranges between 0.05 and 0.23. In this study, the information listed in Table 2 was first used to investigate the relationship between C_T and T (Rossmiller 1980; Chow et al. 1962). The relationship between C_T and T was defined for different land use and land cover in the city of Austin in the United States (Table 2).

This relationship for asphalt and grass cover (50–75% with slope 0–2%) is demonstrated in Fig. 1.

According to Table 2, for all land uses, regressions models were applied for C_T and T and the best regression equation was nonlinear power. Here and based on the data in Table 2, the following equation is suggested for estimating C_T is as it follows:

$$C_T = C_5(T)^a \tag{14}$$

According to Eq. 14, by knowing the 5-year runoff coefficient, which is close to the basin RC (RC in hydrologic tables), the C_T can be determined for each return period.

Power a is of special importance in Eq. 14, which is related to the soil type and vegetation cover.

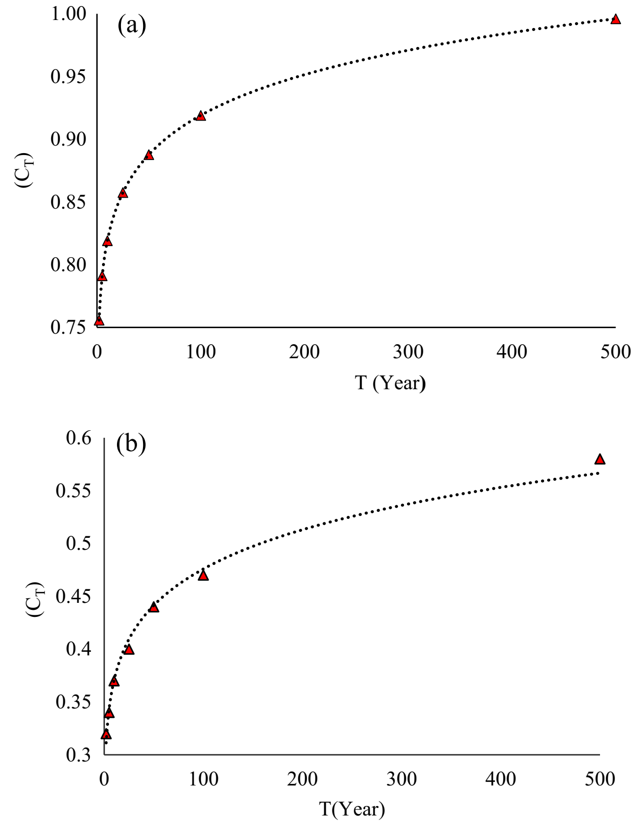

Fig. 1 Relationship between design runoff coefficient (C_t) and return period (T) for **a** asphalt cover and **b** gross cover (50–75% with slope 0–2%)

The values a and correlation coefficients (R) for Eq. 14 in different land uses are present in the second column of Table 2. Based on the results, the correlation coefficients for 20 different land uses were above 0.9, which is a very good result. The coefficient a was observed between 0.05 and 0.12.

Three types of slopes, 0–2%, 2–7%, and above 7%, have been considered for grass cover. The higher slope, the lower infiltration rate, and the RC increases. The higher slope, the lower coefficient a. In forest/woodlands, where the infiltration is high, the values of RC are low, and the value of a for the slope of 0–2% is equal to 0.12 and decreases with increasing slope, and for slope above 7%, this coefficient reaches 0.08. Finally, based on the results, the value of a for soils with low vegetation and permeability is 0.05, and for the higher permeability approaches to 0.12. For low slopes, a is close to 0.07, and for larger slopes, a is close to 0.12.

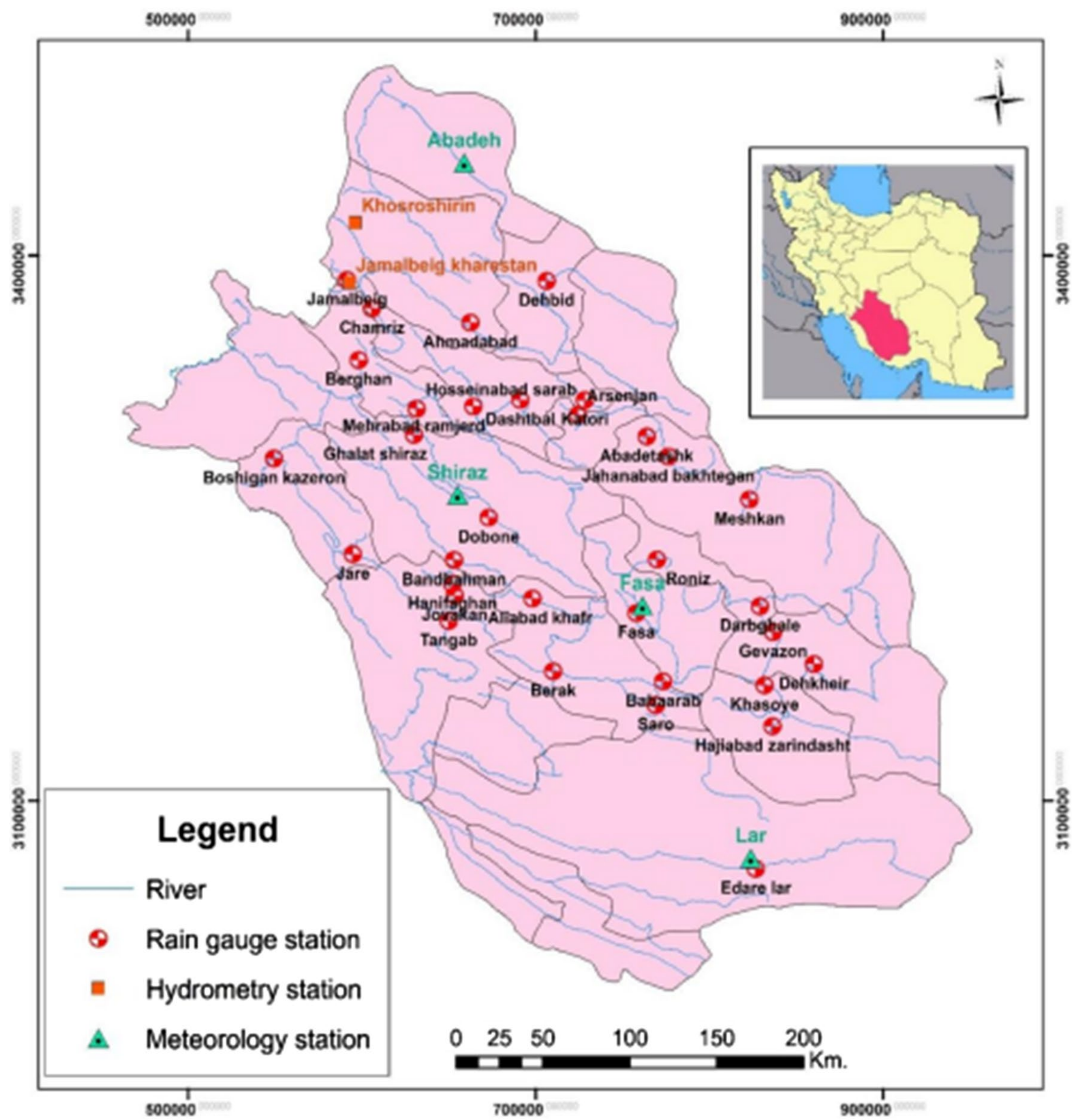

Fig. 2 Study area, location of Fars province in Iran (After Samani, Jamshidi, 2017)

Since the average RC of the basin is close to the 5-year runoff coefficient, by knowing the RC of the basin, C_T can be obtained for different return periods by Eq. 14. In the next part of this research, and the proposed formula will be further validated.

In order to better understand the subject matter, a practical example and methodology were presented in "Appendix A" to explain the method.

6.1 Case Studies

We calculate the C_T for the large area in southern Iran (Fars province) (Fig. 2). Fars is the fourth largest province in Iran (Fig. 2a), with 122,608 km^2 (Torabi Haghighi et al. 2020). The province is located in the southern part of the country, which includes 29 cities and covers 7.5% of Iranian territory. It extends between 27.02° and 31.43°N

Table 3 Used meteorological stations and Rainfall data (After Sabzevari et al. 2009)

Station location	Mean maximum daily	Standard deviation	Mean annual
Abadeh	23.3	11.4	125.43
Izadkhast	31.6	16.2	166.21
Eghlid	31.7	15.2	193.01
Kherameh	33.9	11.9	225.13
Sahl Abad	34.9	15.2	210.49
Jahan Abad Bakhtegan	35.5	12.2	228.32
Ghatrooyeh	35.5	19.5	180.72
Dozhgah	36.5	13.3	167.28
Khosouyeh	38.2	16.9	215.27
Goshnegan Maharloo	38.2	11.9	260.57
Sooriyan	38.5	17.7	197.96
Dehbid	38.8	14.4	227.53
Forg	40.0	21.5	202.67
Neyriz	40.2	23.6	200.41
Mazeyjan Bavanat	40.3	18.9	228.48
Abadeh tashk	40.5	16.5	257.28
Khoorjan	40.7	14.1	261.45
Sheshdeh (Dolat Abad)	41.0	16.6	266.89
Khonj	41.2	15.0	212.79
Baba Arab	41.7	16.7	236.66
Golkoyeh	41.8	7.1	258.33
Darab	42.2	18.8	243.84
Mehrabad Ramjerd	42.7	16.6	347.68
Dehram	42.8	16.7	224.61
Haji Abad Zarindasht	43.2	18.9	227.3
Edareh Lar	43.8	25.9	215.67
Farashband	44.8	18.3	267.5
Khormayek	45.1	18.8	223.4
Ij	45.1	18.3	285.32
Zafar Abad	46.4	20.6	291.93
Khosro Shirin	46.6	20.5	380.27
Hangam	46.9	23.0	259.09
Evaz	47.6	18.2	241.95
Roniz Oliya	47.8	31.3	256.21
Sar mashhad	47.8	17.1	303.52
Khoorab	48.0	17.0	257.83
Fenjan	48.1	18.4	332.83
Hossein Abad Cheshmeh Sara	48.2	13.6	414.66
Dashtbal	48.9	17.5	347.78
Hargan	49.2	23.6	286.78
Shiraz (sazman Ab)	49.3	20.5	355.75
Khan Zenyan	49.5	13.9	453.89
Ali Abad Khafr	49.8	19.8	298.75
Jereh	50.1	20.1	347.91
Arsanjan	50.9	24.3	300.56
Jahrom	50.9	20.3	282.02

Table 3 (continued)

Station location	Mean maximum daily	Standard deviation	Mean annual
Doshman Ziari	51.1	17.6	403.61
Dobaneh	52.4	20.0	381.78
Nargesi	52.5	26.4	327.79
Sedeh	53.1	22.6	456.97
Doroodzan	53.2	19.8	417.11
Darb e Ghaleh	53.9	24.7	291.21
Ahmadabad Chahar Dangeh	54.1	22.1	432.47
Fahlian	54.6	22.1	500.01
Gozoon	54.7	22.8	321.02
Hanifghan	54.8	17.4	435.31
Dashtak	55.0	21.3	483.57
Edare Firouzabad	55.1	15.1	382.34
Lamerd	55.2	23.5	221.2
Hakan	55.3	21.3	303.97
Sabz Pooshan	55.6	17.7	376.73
Galeh Dar	56.4	21.9	248.76
Fasa	56.5	31.7	289.31
Bande Bahman	56.7	19.5	461.76
Mianjangal	57.4	20.2	355.35
Joakan	57.6	20.6	383.56
Kazeroon	60.5	22.7	473.02
Ali Abad Khoshk	61.7	22.3	492.93
Shool Band e Amir	61.8	23.8	343.17
Estahban	62.6	30.1	332.61
Ghalat shiraz	63.0	22.3	554.92
Khollar	63.6	20.9	605.39
Emamzadeh Esmaeil	63.7	23.9	487.86
Gordeh Estahban	65.1	27.1	356.53
Kaftar	66.0	25.2	478.62
Ghaemiyeh	67.7	24.0	565.07
Tangab Firouzabad	69.7	26.0	486.42
Ghatar Aghaj	70.3	20.2	761.78
Choobkhaleh	77.2	25.9	826.58
Dasht Arzhan	78.2	30.2	767.25
Darab	82.0	41.0	513.45
Khergheh	85.1	27.4	581.15
Komehr	95.2	39.5	1011.21

Table 4 Rainfall classification of different regions of Fars province

Type	24-h Rainfall (mm)	Mean max 24-h rainfall(mm)	Standard deviation(mm)
1	0–50	42	17.5
2	50–70	58	22.5
3	70–90	79	29
4	90–110	95	40

Table 5 Design runoff coefficient (C_T) for the region #1 to region #4 in Fars province

Region1: stations with less than 50 mm in maximum daily rainfall

T (year)	CN = 30	40	50	60	70	80	90	CN = 100
5	0.00	0.00	0.00	0.04	0.14	0.30	0.57	1.00
10	0.00	0.00	0.01	0.07	0.19	0.36	0.62	1.00
15	0.00	0.00	0.02	0.09	0.21	0.39	0.64	1.00
20	0.00	0.00	0.03	0.11	0.23	0.41	0.66	1.00
25	0.00	0.00	0.03	0.12	0.24	0.42	0.67	1.00
50	0.00	0.00	0.05	0.15	0.28	0.46	0.70	1.00
100	0.00	0.01	0.07	0.18	0.32	0.50	0.72	1.00
200	0.00	0.02	0.09	0.20	0.35	0.52	0.74	1.00
250	0.00	0.02	0.10	0.21	0.36	0.53	0.75	1.00
500	0.00	0.04	0.12	0.24	0.39	0.56	0.76	1.00
1000	0.00	0.05	0.14	0.26	0.41	0.58	0.78	1.00

Region #2 in Fars province in stations with daily rainfall between 50 and 70 mm

T (year)	CN = 20	30	40	50	60	70	80	90	CN = 100
5	0.00	0.00	0.00	0.03	0.10	0.23	0.41	0.65	1.00
10	0.00	0.00	0.00	0.05	0.15	0.28	0.46	0.70	1.00
15	0.00	0.00	0.01	0.07	0.17	0.31	0.49	0.71	1.00
20	0.00	0.00	0.01	0.08	0.19	0.33	0.51	0.73	1.00
25	0.00	0.00	0.02	0.09	0.20	0.34	0.52	0.73	1.00
50	0.00	0.00	0.03	0.12	0.23	0.38	0.55	0.76	1.00
100	0.00	0.00	0.05	0.14	0.26	0.41	0.58	0.78	1.00
200	0.00	0.01	0.07	0.17	0.29	0.44	0.61	0.79	1.00
250	0.00	0.01	0.07	0.18	0.30	0.45	0.62	0.80	1.00
500	0.00	0.01	0.09	0.20	0.33	0.48	0.64	0.81	1.00
1000	0.00	0.02	0.11	0.22	0.36	0.50	0.66	0.82	1.00

Region #3 in Fars province in stations with daily rainfall between 70 and 90 mm

T (year)	CN = 20	30	40	50	60	70	80	90	CN = 100
5	0.00	0.00	0.01	0.08	0.19	0.33	0.50	0.73	1.00
10	0.00	0.00	0.03	0.12	0.23	0.38	0.55	0.76	1.00
15	0.00	0.00	0.05	0.14	0.26	0.41	0.58	0.77	1.00
20	0.00	0.00	0.06	0.15	0.28	0.42	0.59	0.78	1.00
25	0.00	0.00	0.06	0.16	0.29	0.44	0.60	0.79	1.00
50	0.00	0.01	0.09	0.19	0.32	0.47	0.63	0.81	1.00
100	0.00	0.02	0.11	0.22	0.36	0.50	0.66	0.83	1.00
200	0.00	0.04	0.13	0.25	0.39	0.53	0.68	0.84	1.00
250	0.00	0.04	0.14	0.26	0.40	0.54	0.69	0.84	1.00
500	0.00	0.06	0.16	0.29	0.42	0.56	0.71	0.85	1.00
1000	0.00	0.07	0.18	0.31	0.45	0.58	0.72	0.86	1.00

Region #4 in Fars province in stations with daily rainfall between 90 and 110 mm

T (year)	CN = 20	30	40	50	60	70	80	90	CN = 100
5	0.00	0.00	0.04	0.13	0.25	0.40	0.57	0.77	1.00
10	0.00	0.01	0.08	0.18	0.31	0.46	0.62	0.80	1.00
15	0.00	0.02	0.09	0.21	0.34	0.48	0.64	0.82	1.00
20	0.00	0.02	0.11	0.22	0.36	0.50	0.66	0.82	1.00
25	0.00	0.03	0.12	0.24	0.37	0.51	0.67	0.83	1.00
50	0.00	0.05	0.15	0.27	0.41	0.55	0.70	0.85	1.00

Table 5 (continued)

Region #4 in Fars province in stations with daily rainfall between 90 and 110 mm									
T (year)	CN = 20	30	40	50	60	70	80	90	CN = 100
100	0.00	0.07	0.18	0.31	0.44	0.58	0.72	0.86	1.00
200	0.01	0.09	0.21	0.34	0.47	0.61	0.74	0.87	1.00
250	0.01	0.09	0.22	0.35	0.48	0.62	0.75	0.88	1.00
500	0.02	0.11	0.24	0.38	0.51	0.64	0.76	0.88	1.00
1000	0.02	0.13	0.27	0.40	0.53	0.66	0.78	0.89	1.00

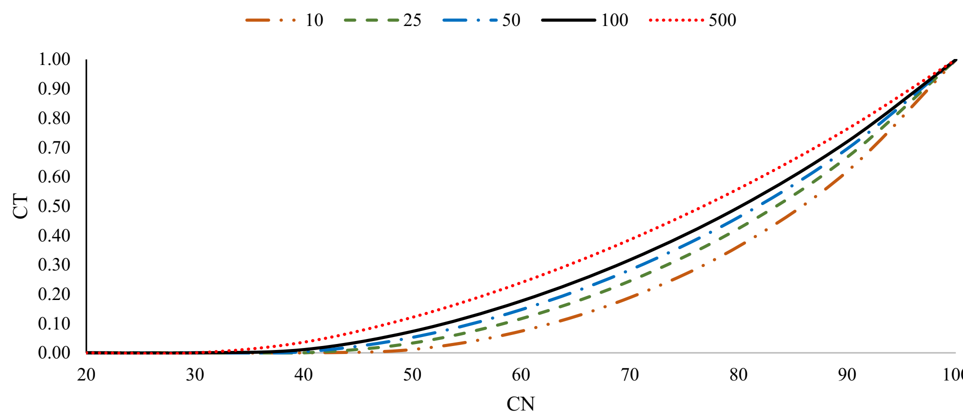

Fig. 3 Variation of design run-off coefficient (C_T) for different CN values and return periods for region 1

Table 6 Designed runoff coefficient (C_T) for different land uses and different return periods in Region 1

Land use description		Return period				
		10	25	50	100	500
Cultivated land: without conservation treatment		0.22–0.65	0.28–0.70	0.31–0.72	0.35–0.74	0.42–0.78
With conservation treatment		0.09–0.38	0.14–0.44	0.17–0.48	0.20–0.52	0.27–0.58
Pasture or range land: poor condition		0.16–0.59	0.22–0.64	0.25–0.67	0.29–0.69	0.35–0.74
Good condition		0.00–0.36	0.00–0.42	0.00–0.46	0.01–0.50	0.03–0.56
Meadow: good condition		0.00–0.32	0.00–0.38	0.00–0.42	0.00–0.46	0.00–0.52
Wood or forest land: thin stand, poor cover, no mulch		0.00–0.43	0.01–0.49	0.02–0.53	0.04–0.56	0.07–0.62
Good cover		0.00–0.30	0.00–0.36	0.00–0.40	0.00–0.44	0.00–0.50
Open spaces, lawns, parks, golf courses, cemeteries, etc						
Good condition: grass cover on 75% or more of the area		0.00–0.36	0.00–0.42	0.00–0.46	0.01–0.50	0.03–0.56
Fair condition: grass cover on 50% to 75% of the area		0.01–0.45	0.03–0.51	0.05–0.55	0.06–0.58	0.11–0.64
Commercial or business areas (85% impervious)		0.59–0.79	0.64–0.82	0.67–0.84	0.69–0.85	0.74–0.88
Industrial districts (72% impervious)		0.38–0.72	0.44–0.76	0.48–0.78	0.52–0.80	0.58–0.83
Residential:						
Average lot size	Average % impervious					
1/8acre or less	65	0.30–0.68	0.36–0.73	0.40–0.75	0.44–0.77	0.50–0.81
1/4 acre	38	0.08–0.53	0.13–0.59	0.16–0.62	0.19–0.65	0.25–0.70
1/3 acre	30	0.05–0.50	0.09–0.56	0.11–0.59	0.14–0.62	0.20–0.68
½ acre	25	0.03–0.48	0.06–0.54	0.09–0.57	0.11–0.60	0.16–0.66
1 acre	20	0.02–0.45	0.04–0.51	0.06–0.55	0.08–0.58	0.13–0.64
Paved parking lot, roofs, driveways, etc		0.91–0.91	0.92–0.92	0.93–0.93	0.94–0.94	0.95–0.95
Street and roads:						
Paved with curbs and storm sewers		0.91–0.91	0.92–0.92	0.93–0.93	0.94–0.94	0.95–0.95
Gravel		0.28–0.65	0.35–0.70	0.38–0.72	0.42–0.74	0.49–0.78
Dirt		0.22–0.59	0.28–0.64	0.31–0.67	0.35–0.69	0.42–0.74

Table 7 Land use-based value of Designed runoff coefficient (C_T) for different land uses and different return periods in Region 2

Land use description		Return period				
		10	25	50	100	500
Cultivated land: without conservation treatment		0.31–0.72	0.37–0.76	0.41–0.78	0.44–0.80	0.51–0.83
With conservation treatment		0.17–0.48	0.22–0.54	0.26–0.57	0.29–0.60	0.36–0.65
Pasture or range land: poor condition		0.25–0.67	0.31–0.71	0.34–0.73	0.38–0.76	0.44–0.79
Good condition		0.00–0.46	0.01–0.52	0.03–0.55	0.04–0.58	0.08–0.64
Meadow: good condition		0.00–0.42	0.00–0.48	0.00–0.51	0.00–0.54	0.01–0.60
Wood or forest land: thin stand, poor cover, no mulch		0.02–0.52	0.05–0.58	0.07–0.61	0.09–0.64	0.14–0.69
Good cover		0.00–0.40	0.00–0.46	0.00–0.49	0.00–0.53	0.00–0.59
Open spaces, lawns, parks, golf courses, cemeteries, etc						
Good condition: grass cover on 75% or more of the area		0.00–0.46	0.01–0.52	0.03–0.55	0.04–0.58	0.08–0.64
Fair condition: grass cover on 50% to 75% of the area		0.04–0.55	0.08–0.60	0.10–0.63	0.13–0.66	0.19–0.70
Commercial or business areas (85% impervious)		0.67–0.84	0.71–0.86	0.73–0.87	0.76–0.88	0.79–0.90
Industrial districts (72% impervious)		0.48–0.78	0.54–0.81	0.57–0.83	0.60–0.84	0.65–0.87
Residential:						
Average lot size	Average % impervious					
1/8 acre or less	65	0.40–0.75	0.46–0.78	0.49–0.80	0.53–0.82	0.59–0.85
1/4 acre	38	0.16–0.62	0.21–0.66	0.24–0.69	0.28–0.71	0.34–0.76
1/3 acre	30	0.11–0.59	0.16–0.64	0.19–0.67	0.22–0.69	0.29–0.74
½ acre	25	0.08–0.57	0.13–0.62	0.16–0.65	0.19–0.67	0.25–0.72
1 acre	20	0.06–0.55	0.10–0.60	0.12–0.63	0.15–0.66	0.21–0.70
Paved parking lot, roofs, driveways, etc		0.93–0.93	0.94–0.94	0.95–0.95	0.95–0.95	0.96–0.96
Street and roads:						
Paved with curbs and storm sewers		0.93–0.93	0.94–0.94	0.95–0.95	0.95–0.95	0.96–0.96
Gravel		0.38–0.72	0.44–0.76	0.48–0.78	0.51–0.80	0.57–0.83
Dirt		0.31–0.67	0.37–0.71	0.41–0.73	0.44–0.76	0.51–0.79

Table 8 Land use-based value of Designed runoff coefficient (C_T) for different land uses and different return periods in Region 3

Land use description		Return period				
		10	25	50	100	500
Cultivated land: without conservation treatment		0.41–0.78	0.47–0.81	0.50–0.83	0.53–0.84	0.59–0.87
With conservation treatment		0.26–0.57	0.31–0.62	0.35–0.65	0.38–0.67	0.45–0.72
Pasture or range land: poor condition		0.35–0.74	0.40–0.77	0.44–0.79	0.47–0.81	0.53–0.84
Good condition		0.03–0.55	0.05–0.60	0.08–0.63	0.10–0.66	0.15–0.71
Meadow: good condition		0.00–0.51	0.00–0.57	0.01–0.60	0.02–0.63	0.05–0.68
Wood or forest land: thin stand, poor cover, no mulch		0.07–0.61	0.11–0.66	0.14–0.68	0.16–0.71	0.22–0.75
Good cover		0.00–0.50	0.00–0.55	0.00–0.58	0.00–0.61	0.02–0.66
Open spaces, lawns, parks, golf courses, cemeteries, etc						
Good condition: grass cover on 75% or more of the area		0.03–0.55	0.05–0.60	0.08–0.63	0.10–0.66	0.15–0.71
Fair condition: grass cover on 50% to 75% of the area		0.11–0.63	0.15–0.67	0.18–0.70	0.21–0.72	0.27–0.76
Commercial or business areas (85% impervious)		0.74–0.87	0.77–0.89	0.79–0.90	0.81–0.91	0.84–0.93
Industrial districts (72% impervious)		0.57–0.83	0.62–0.85	0.65–0.86	0.67–0.88	0.72–0.90
Residential:						
Average lot size	Average % impervious					
1/8 acre or less	65	0.50–0.80	0.55–0.83	0.58–0.85	0.61–0.86	0.66–0.88
¼ acre	38	0.25–0.69	0.30–0.73	0.34–0.75	0.37–0.77	0.43–0.81
1/3 acre	30	0.19–0.67	0.25–0.71	0.28–0.74	0.31–0.76	0.38–0.79
½ acre	25	0.16–0.65	0.21–0.69	0.24–0.72	0.27–0.74	0.34–0.78
1 acre	20	0.13–0.63	0.17–0.67	0.20–0.70	0.24–0.72	0.30–0.76
Paved parking lot, roofs, driveways, etc		0.95–0.95	0.96–0.96	0.96–0.96	0.96–0.96	0.97–0.97
Street and roads:						
Paved with curbs and storm sewers		0.95–0.95	0.96–0.96	0.96–0.96	0.96–0.96	0.97–0.97
Gravel		0.48–0.78	0.53–0.81	0.57–0.83	0.59–0.84	0.65–0.87
Dirt		0.41–0.74	0.47–0.77	0.50–0.79	0.53–0.81	0.59–0.84

latitude and 50.42°–55.36°E longitude. The province includes different climates due to geographical configuration and position between the high Zagros Mountain in the north and west, the Sirjan desert in the north and east, and the Persian Gulf in the south (Torabi Haghighi et al. 2020). This study used the daily rainfalls of 83 rain gauge stations in Fars province (Table 3 in the supplementary material (S.M.)). Previous studies illustrated that the Gumbel distribution is the best-fitted distribution for maximum daily rainfall (Ahmadpour et al. 2017).

Based on the variation of daily rainfall, the Fars province is divided into four regions (Table 4 and Fig. 2.b).

7 Results and Discussion

7.1 Design Runoff Coefficient *CT* for Fars Province

In the first region of Fars province (region 1), 83 rain gauge stations with maximum daily rainfall of less than 50 mm were analyzed. In this region, the mean and standard deviation of rainfall was 42 mm and 17.5 mm, respectively. The C_T for different return periods from 5 to 1000 years and variation in CN from 30 (for highly permeable soils) to 100 (for low permeable soils) were calculated based on Eq. 10 and considering the Gumbel distribution. In this region, the C_T for high permeable soil (CN below 40) is zero, and for CN = 40 only for 100 years return period, we have C_T lower than 0.05. For permeable soil (i.e., CN = 70), the C_T varied between 0.14 and 0.41, while for low permeable soils (i.e., CN = 90), it varied between 0.57 and 0.78 (Table 5).

Figure 3 shows the variation of design runoff coefficient (CT) for different CN values and return periods for region1 based on Table 5. As the value of CN represented the hydrological group based on land use and permeability of the soil, e.g., group A represents permeable, and group *D* is representative of low permeable soils (look at Table 1), we can provide the C_T variation for different land use and return period (Table 6). Based on these results, the C_T for meadowland use in good condition will be varied between 0 and 0.32 for 10 years return period.

Furthermore, for other regions (regions 2–4), the CN- based (same as Table 5) and land-use-based (same as Table 6) tables of C_T are produced and illustrated in Tables 5, 6, 7, 8, 9, 10 in SM.

Table 9 Land use-based value of Designed runoff coefficient (C_T) for different land uses and different return periods in Region 4

Land use description		Return period				
		10	25	50	100	500
Cultivated land: without conservation treatment		0.49–0.82	0.54–0.85	0.58–0.86	0.61–0.87	0.66–0.90
With conservation treatment		0.34–0.64	0.40–0.68	0.44–0.71	0.47–0.73	0.53–0.78
Pasture or range land: poor condition		0.42–0.78	0.48–0.81	0.52–0.83	0.55–0.85	0.61–0.87
Good condition		0.07–0.62	0.11–0.67	0.14–0.70	0.17–0.72	0.23–0.76
Meadow: good condition		0.01–0.59	0.03–0.64	0.05–0.67	0.07–0.69	0.11–0.74
Wood or forest land: thin stand, poor cover, no mulch		0.12–0.67	0.17–0.72	0.21–0.74	0.24–0.76	0.31–0.80
Good cover		0.00–0.57	0.00–0.62	0.01–0.65	0.02–0.68	0.06–0.73
Open spaces, lawns, parks, golf courses, cemeteries, etc						
Good condition: grass cover on 75% or more of the area		0.07–0.62	0.11–0.67	0.14–0.70	0.17–0.72	0.23–0.76
Fair condition: grass cover on 50–75% of the area		0.17–0.69	0.22–0.73	0.26–0.76	0.29–0.78	0.36–0.81
Commercial or business areas (85% impervious)		0.78–0.90	0.81–0.91	0.83–0.92	0.85–0.93	0.87–0.94
Industrial districts (72% impervious)		0.64–0.86	0.68–0.88	0.71–0.89	0.73–0.90	0.78–0.92
Residential:						
Average lot size	Average % impervious					
1/8 acre or less	65	0.57–0.84	0.62–0.86	0.65–0.88	0.68–0.89	0.73–0.91
¼ acre	38	0.32–0.74	0.38–0.78	0.42–0.80	0.46–0.82	0.52–0.85
1/3 acre	30	0.27–0.73	0.33–0.76	0.37–0.79	0.40–0.80	0.47–0.84
½ acre	25	0.23–0.71	0.29–0.75	0.32–0.77	0.36–0.79	0.43–0.82
1 acre	20	0.19–0.69	0.25–0.73	0.29–0.76	0.32–0.78	0.39–0.81
Paved parking lot, roofs, driveways, etc		0.96–0.96	0.97–0.97	0.97–0.97	0.97–0.97	0.98–0.98
Street and roads:						
Paved with curbs and storm sewers		0.96–0.96	0.97–0.97	0.97–0.97	0.97–0.97	0.98–0.98
Gravel		0.55–0.82	0.61–0.85	0.64–0.86	0.66–0.87	0.71–0.90
Dirt		0.49–0.78	0.54–0.81	0.58–0.83	0.61–0.85	0.66–0.87

Table 10 CN-based value of α coefficients for different regions of Fars provinces

CN	20	30	40	50	60	70	80	90
								Region 1
a	–	–	–	–	0.29	0.17	0.10	0.05
R	–	–	–	–	0.92	0.95	0.94	0.93
								Region 2
a	–	–	–	0.31	0.19	0.12	0.07	0.04
R	–	–	–	0.93	0.96	0.95	0.94	0.93
								Region3
a	–	–	0.45	0.21	0.13	0.09	0.06	0.03
R	–	–	0.80	0.96	0.95	0.95	0.94	0.92
								Region4
a	–	–	0.29	0.17	0.12	0.08	0.05	0.02
R	–	–	0.92	0.95	0.95	0.94	0.93	0.91

7.2 CN-Based Value of "*a*" Coefficients for Different Regions

The *a* coefficient (in Eq. 14) was calculated from 0.05 to 0.12 for the low permeable soils to high permeable soils. Here, we will validate *a* coefficient for different regions based on the calculated C_T in different regions in the previous part (e.g., data in Table 5 for region 1 and region 2). By using SPSS16 software and mentioned data (in Table 5), Eq.14 was re-evaluated, and

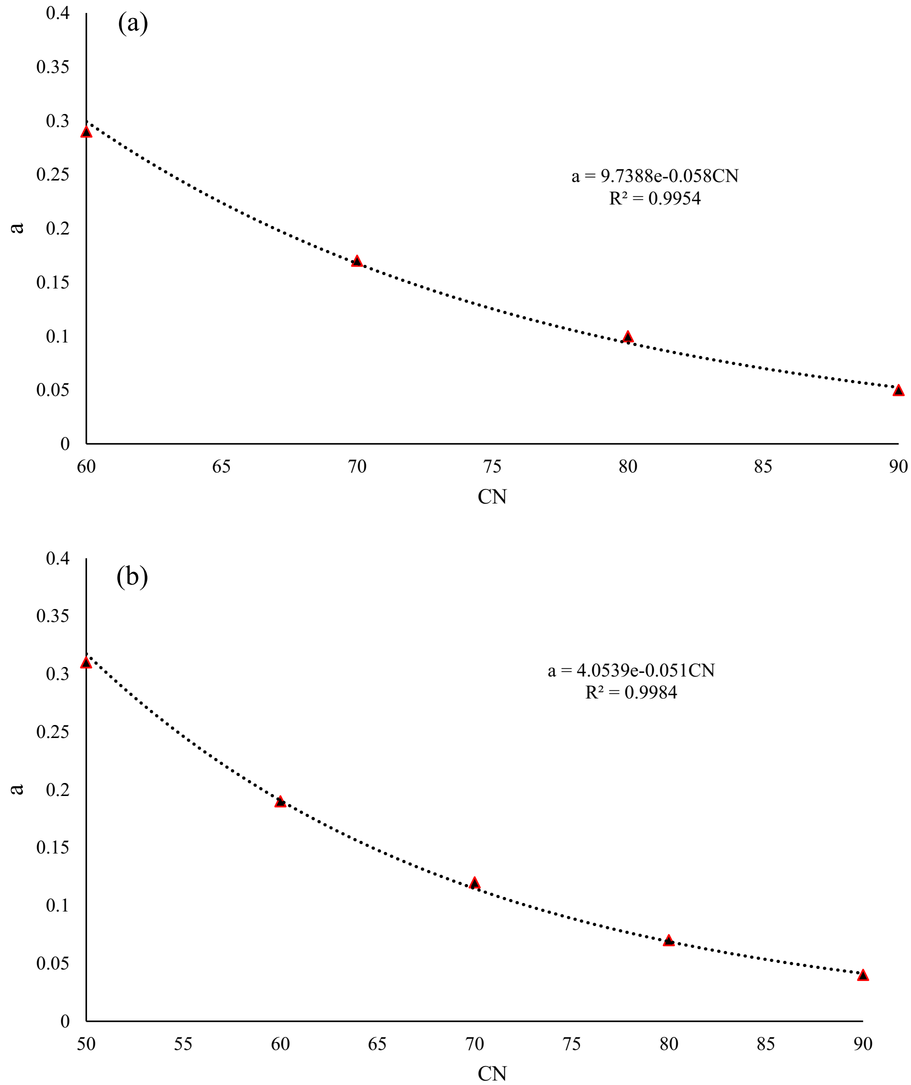

Fig. 4 Relationship between CN and *a* for **a** regions 1, **b** region 2

the optimal nonlinear regression coefficients (a, R) were calculated (Table 10).

For region 1, the a coefficient ranged from 0.05 to 0.29 for CN variation from 90 to 60 with a significant correlation coefficient of more than 0.92 (Fig. 4a).

Finally following Eqs were suggested for estimating a value in different regions 1–4 of Fars province.

$$a(Region1) = 9.74 \times e^{-0.058 \times CN} \quad (15)$$

$$a(Region2) = 4.10 \times e^{-0.051 \times CN} \quad (16)$$

$$a(Region3) = 2.98 \times e^{-0.050 \times CN} \quad (17)$$

$$a(Region2) = 2.25 \times e^{-0.050 \times CN} \quad (18)$$

8 Conclusion

One method for calculating the runoff of small catchments, in particular in urban areas, is the rational method. The rational method includes a function of the catchment's area, storm intensity, and runoff coefficient. Urban drainage system engineers use the notion of a design return period to design surface runoff disposal systems such as canals and drains.

The design runoff coefficient should be increased according to the return period of the structure design. The runoff coefficient hinges on the catchment's slope, plant cover, and land use of the catchment. These pieces of information are usually available in the catchments.

The initial idea of this research was to formulate the design runoff coefficient on the basis of the rainfall and land use data of each catchment in the world, and to calculate it separately so that the flood estimation can be performed more accurately using the rational method.

In this study, we present a novel approach for correcting design runoff coefficients for different return periods. The regional design runoff coefficient was computed based on a statistical analysis of local maximum daily rainfall in our technical approach. The method applied for Fars province in Iran was divided into four regions based on the observed historical value of maximum daily rainfall of 83 rainfall stations. CN and land use-based runoff coefficient tables were derived for different return periods from 10 to 500 years for each region. Finally, equations were introduced where the design runoff coefficient is a function of the return period and the curve number.

The runoff coefficient for different return periods from 5 to 1000 years and variation in CN from 30 (for highly permeable soils) to 100 (for low permeable soils) were calculated based on proposed equations.

The design runoff coefficient equation was presented as $C_T = C_5(T)^a$. The coefficient "a" was presented as a function of the curve number in 4 different regions in Fars province.

According to the proposed equation, it is possible to transform the standard curve number tables, which are widely used in flood prediction using the SCS method, into tables for calculating the design runoff coefficient. These tables were calculated and provided for the Fars region.

The method can be reproduced for other regions worldwide and be in service of local water authorities and consulting engineering companies to use in rainfall-runoff studies for gauged and ungauged basins. It is suggested that the results of this research and the proposed method in different basins or different climates be evaluated and validated based on observed rainfall and runoff data of the basins to further evaluate the effect of considering the return period on runoff coefficient in the rational method.

Appendix A

Methodology Algorithm

The summary methodology of the research with the practical example is as follows:

1. First, determine the maximum daily rainfall of the basin for different return periods (P_T) using statistical distribution or intensity–duration–frequency curves.
2. According to the vegetation, soil type and land use of the basin, the average value of curve number (CN) should be determined.
3. The value of the design runoff coefficient for each return period is calculated from the following equation:

$$C_T = \frac{\left(P_T - 0.2SR\right)^2}{P_T\left(P_T + 0.8SR\right)}, SR = \left(\frac{25400}{CN} - 254\right)$$

Example: In one of the cities of Fars province, the average daily rainfall for 40 statistical years and the standard deviation are, respectively, 40 mm and 10 mm. If the Gumbel distribution is the best distribution according to the rainfall data and the land use is urban with vegetation CN = 88, calculate the regional runoff coefficient with a return period of 100 years.

Solution:

The 100-year design rainfall amount according to Gumble statistical distribution is equal to:

$$K_T = -\frac{\sqrt{6}}{\Pi}\left[0.5772 + ln\left(ln\left(\frac{100}{100-1}\right)\right)\right] = 3.136$$

$$P_{100} = \bar{P} + K_{100}s = 40mm + 10 \times 3.136 = 71.36mm$$

The 100-year runoff coefficient is equal to:

$$SR = \left(\frac{25400}{CN = 88} - 254\right) = 34.63mm$$

$$C_{100} = \frac{\left(P_{100} - 0.2SR\right)^2}{P_{100}\left(P_{100} + 0.8SR\right)} = \frac{(71.36 - 0.2 \times 34.63)^2}{71.36(71.36 + 0.8 \times 34.63)} = 0.587$$

If rainfall data are not available in the area, the runoff coefficient of this city is computed using the following method.

The average rainfall in the city is 40 mm, and if the amount of rainfall is assumed to be 40 mm, the region is of type 1. So, the equations for estimating the runoff coefficient equal to100 are as follows.

If the runoff coefficient of the city is equal to 0.77 according to the runoff coefficient tables for the return period of 5 years, the 100-year runoff coefficient would be:

$$C_{T=100} = C_5\left(T\right)^a = 0.77 \times \left(100\right)^{0.059} = 1\big)\big)$$

$$a(Region1) = 9.74 \times e^{-0.058\times(CN=88)} = 0.059$$

Declarations

Conflict of interest Authors have no conflict of interest to declare.

Consent to Participate Not applicable.

Consent for Publication Not applicable.

Ethics Approval Not applicable.

References

Apollonio C, Rose MD, Fidelibus C, Orlanducci L, Spasiano D (2018) Water management problems in a karst flood-prone endorheic basin. Environ Earth Sci 77(19):676

Al-Amri NS, Ewea HA, Elfeki AM (2022) Revisit the rational method for flood estimation in the Saudi arid environment. Arab J Geosci 15(6):532

Akan AO (2002) Modified rational method for sizing infiltration structures. Can J Civ Eng 29(4):539–542

Ahmadpour A, Fathian H, Haghighatjoo P (2017) Frequency analysis of maximum daily rainfall in various climates of Iran. J Water Sci Eng 7(16):49–60

Ardekani AA, Sabzevari T, Haghighi AT (2021) Separation of surface flow from subsurface flow in catchments using runoff coefficient. Acta Geophys 69:2363–2376. https://doi.org/10.1007/s11600-021-00667-6

ASCE, and Water Pollution Control Federation (WPCF) (1960) Design and construction of sanitary and storm sewers. ASCE, Reston, VA

Bernard M (1938) Modified rational method of estimating flood flows. Natural Resources Commission, Washington

Baiamonte G (2020) A rational runoff coefficient for a revisited rational formula. Hydrol Sci J 65(1):112–126

Courty LG, Wilby RL, Hillier JK, Slater LJ (2019) Intensity-duration-frequency curves at the global scale. Environ Res Lett 14(8):084045

Chin D (2013) Water-resources engineering, 3rd edn. Pearson, Upper Saddle River

Chin DA (2017) Discussion of "return period–dependent rational formula coefficients for two locations in Texas" by David C. Froehlich. J Irrig Drain Eng 143(9):07017014

Chow V, Maidment DR, Mays LW (1962) Applied hydrology. J Eng Educ 308:1959

Chin DA (2019) Estimating peak runoff rates using the rational method. J Irrig Drain Eng 145(6):04019006

Cleveland TG, Thompson DB, Fang X (2011) Use of the rational and modified rational method for hydraulic design (No. FHWA/TX-08/0-6070-1).

Dunne T, Zhang W, Aubry BF (1991) Effects of rainfall, vegetation, and microtopography on infiltration and runoff. Water Resour Res 27(9):2271–2285

Dunkerley D (2012) Effects of rainfall intensity fluctuations on infiltration and runoff: rainfall simulation on dryland soils, Fowlers Gap, Australia. Hydrol Process 26(15):2211–2224

Dhakal N, Fang X, Cleveland TG, Thompson DB, Marzen LJ (2010) Estimation of rational runoff coefficients for Texas watersheds. In: World environmental and water resources congress 2010: challenges of change, pp 3339–3348

Dhakal N et al (2012) Estimation of volumetric runoff coefficients for Texas watersheds using land-use and rainfall-runoff data. J Irrig Drain Eng ASCE 138:43–54. https://doi.org/10.1061/(ASCE)IR.1943-4774.0000368

Dhakal N, Fang X, Asquith WH, Cleveland TG, Thompson DB (2013) Return period adjustment for runoff coefficients based on analysis in undeveloped Texas watersheds. J Irrig Drain Eng 139(6):476–482

Fariborzi H, Sabzevari T, Noroozpour S, Mohammadpour R (2019) Prediction of the subsurface flow of hillslopes using a subsurface time-area model. Hydrogeol J 27(4):1401–1417

Froehlich DC (2016) Return period–dependent rational formula coefficients for two locations in Texas. J Irrig Drain Eng 142(9):04016035

Ghahraman B, Abkhezr H (2004) Improvement in intensity-duration-frequency relationships of rainfall in Iran. JWSS Isfahan Univ Technol 8(2):1–14

Guo JC (2001) Rational hydrograph method for small urban watersheds. J Hydrol Eng 6(4):352–356

Giordano R, Milella P, Portoghese I, Vurro M, Apollonio C, D'Agostino D, Piccinni AF (2010) An innovative monitoring system for sustainable management of groundwater resources: objectives, stakeholder acceptability and implementation strategy. In: 2010 IEEE workshop on environmental energy and structural monitoring systems. IEEE, pp 32–37

Grimaldi S, Petroselli A (2015) Do we still need the rational formula? An alternative empirical procedure for peak discharge estimation in small and ungauged basins. Hydrol Sci J 60(1):67–77

Hajani E, Rahman A (2018) Design rainfall estimation: comparison between GEV and LP3 distributions and at-site and regional estimates. Nat Hazards 93(1):67–88

Huang J, Wu P, Zhao X (2013) Effects of rainfall intensity, underlying surface and slope gradient on soil infiltration under simulated rainfall experiments. CATENA 104:93–102

Hotchkiss RH, Provaznik MK (1995) Observations on the rational method C value." Watershed management: Planning for the 21st century, T. J. Ward, ed., ASCE, New York, 21–26

Jens SW (1979) Design of urban highway drainage. FHWA Pub. No.TS-79-225, Federal Highway Administration, Washington, DC

Kim NW, Shin MJ (2018) Estimation of peak flow in ungauged catchments using the relationship between runoff coefficient and curve number. Water 10(11):1669

Kuichling E (1889) The relation between the rainfall and the discharge of sewers in populous areas. Trans ASCE 20(1):1–56

Ken-Bohuslav PE (2004) Hydraulic design manual. Texas Department of Transportation (TxDOT) Published by the Design Division (DES)(512), 416–2055

Lapides DA, Sytsma A, Thompson S (2021) Implications of distinct methodological interpretations and runoff coefficient usage for rational method predictions. JAWRA J Am Water Resour Assoc 57(6):859–874

Lu J, Chen X, Zhang L, Sauvage S, Sánchez-Pérez JM (2018) Water balance assessment of an ungauged area in Poyang Lake watershed using a spatially distributed runoff coefficient model. J Hydroinf 20(5):1009–1024

Li MH, Chibber P (2008) Overland flow time of concentration on very flat terrains. Transp Res Rec 2060(1):133–140

Longobardi A, Villani P, Grayson RB, Western AW (2003) On the relationship between runoff coefficient and catchment initial conditions. In: Proceedings of MODSIM, pp 867–872

Machado RE, Cardoso TO, Mortene MH (2022) Determination of runoff coefficient (C) in catchments based on analysis of precipitation and flow events. Int Soil Water Conserv Res 10(2):208–216

Menberu MW, Haghighi AT, Ronkanen AK, Kværner J, Kløve B (2015) Runoff curve numbers for peat-dominated watersheds. J Hydrol Eng 20(4):04014058

Merkel W, Moody H, Quan Q (2017) Design rainfall distributions based on NOAA Atlas 14 rainfall depths and durations. National Water Quality Monitoring Council, New York

Młyński D, Wałęga A, Ozga-Zielinski B, Ciupak M, Petroselli A (2020) New approach for determining the quantiles of maximum annual flows in ungauged catchments using the EBA4SUB model. J Hydrol 589:125198

Mishra SK, Singh VP (2013) Soil conservation service curve number (SCS-CN) methodology, vol 42. Springer, Berlin

Morel-Seytoux H, Verdin J (1981) Extension of soil conservation service rainfall runoff methodology for ungaged watersheds. Rep. FHWA/RD-81/060, Federal Highway Administration,Washington, DC

Madsen H, Arnbjerg-Nielsen K, Mikkelsen PS (2009) Update of regional intensity-duration-frequency curves in Denmark:

tendency towards increased storm intensities. Atmos Res 92(3):343–349

Pishvaei MH, Sabzevari T, Noroozpour S, Mohammadpour R (2020) Effects of hillslope geometry on spatial infiltration using the TOPMODEL and SCS-CN models. Hydrol Sci J 65(2):212–226

Peng Z, Hu W, Liu G, Gao R, Wei W (2019) Estimating daily inflows of large lakes using a water-balance-based runoff coefficient scaling approach. Hydrol Process 33(19):2535–2550

Pilgrim DH, Cordery I (1993) Flood runoff. Handbook of hydrology, D. R. Maidment, ed. McGraw-Hill, New York, pp 91–942

Rossmiller RL (1980) The rational formula revisited. In: Proceedings of international symposium on urban storm runoff (University of Kentucky, Lexington, KY, 28–31)

Sabzevari T (2010) Development of catchments geomorphological instantaneous unit hydrograph based on surface and subsurface flow response of complex hillslopes. PhD dissertation, PhD Thesis, Islamic Azad University, Tehran, Iran

Sabzevari T (2017) Runoff prediction in ungauged catchments using the gamma dimensionless time-area method. Arab J Geosci 10:1–11

Sabzevari T, Ardakanian R, Shamsaee A, Talebi A (2009) Estimation of flood hydrograph in no statistical watersheds using HEC-HMS model and GIS (Case study: Kasilian watershed). J Water Eng 4:1–11

Samani N, Jamshidi Z (2017) Climate change trend in Fars Province, Iran and its effect on groundwater crisis. In: Proceedings of the international conference of recent trends in environmental science and engineering (RTESE'17) Toronto, Canada–August, pp 23–25

Schaake JC, Geyer JC, Knapp JW (1967) Experimental examination of the rational method. J Hydraul Div 93(6):353–370

Soltani S, Helfi R, Almasi P, Modarres R (2017) Regionalization of rainfall intensity-duration-frequency using a simple scaling model. Water Resour Manag 31(13):4253–4273

Sriwongsitanon N, Taesombat W (2011) Effects of land cover on runoff coefficient. J Hydrol 410(3–4):226–238

Titmarsh GW, Cordery I, Pilgrim DH (1995) Calibration procedures for rational and USSCS design flood methods. J Hydraul Eng. https://doi.org/10.1061/(ASCE)0733-9429(1995)121:1(61),61-70

Torabi Haghighi A, Zaki NA, Rossi PM, Noori R, Hekmatzadeh AK, Saremi H, Kløve B (2020) Unsustainability syndrome-from meteorological to agricultural drought in arid and semi-arid regions. Water 12(3):838. https://doi.org/10.3390/w12030838

Young CB, McEnroe BM, Rome AC (2009) Empirical determination of rational method runoff coefficients. J Hydrol Eng 14(12):1283–1289

Zhang Z, Chen X, Huang Y, Zhang Y (2014) Effect of catchment properties on runoff coefficient in a karst area of southwest China. Hydrol Process 28(11):3691–3702