Calibration of seasonal transfer equation (Z–R) by data of Doppler weather radar, rainfall gauging station and genetic algorithm method in the Abolabbas watershed (in southwest of Iran)

Arash Adib, Masoud Soori Damirchi Sofla, Seyed Yahya Mirzaei, Mohammad Mahmoudian Shoushtari and Ali Liaghat

ABSTRACT

The observed radar reflectivity (Z) converts to rainfall intensity (R) by a transfer function. In the first stage, for calibration of collected data (with time step 15 minutes) by weather radar and determination of the best relation between Z and R, it applied a genetic algorithm (GA) to minimize the amount of root mean square error (RMSE). Although $Z = 166R^2$ (the transfer function in the Khuzestan province of Iran) is an appropriate equation, the GA method distinguished that $Z = 110R^{1.8}$ (from February to May) and $Z = 126R^2$ (for other months) are the optimum transfer functions for the Abolabbas watershed in Iran. The mean of RMSE of optimum transfer equations is 0.59 mm/hr in the calibration stage and 0.85 mm/hr in the verification stage. In the second stage, the Hydrologic Modeling System (HEC-HMS model) used four types of precipitation data (extracted rainfall data from radar and the optimum transfer equations, $Z = 166R^2$, $Z = 200R^{1.6}$ and extracted rainfall data from rainfall gauging stations). The calibrated rainfall data by the optimum transfer equations can produce flood hydrographs in which their accuracy is similar to the accuracy of generated flood hydrographs by collected rainfall data of rainfall gauging stations. The mean of RMSE is 0.65 cubic metres per second and the mean or R^2 is 0.89 for optimum transfer equations.

Key words | Abolabbas watershed, Doppler weather radar, genetic algorithm, HEC-HMS rainfall–runoff model, transfer function Z–R

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HIGHLIGHTS

- Extraction of the function Z–R for a watershed.
- Using time intervals less than 1 hr for rainfall hyetographs (15 minutes).
- Using an optimization method for determination of the transfer function Z–R and considering seasonal characteristics of precipitation that can distinguish two transfer functions Z–R.
- Using a rainfall–runoff model for determination of accuracy of the derived functions Z–R.

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INTRODUCTION

The use of technologies and tools as weather radars and satellite images for measurement of meteorological phenomena (temperature, precipitation, etc.) is a conventional method in developed countries. But in developing countries, the use of these tools is new approach. Therefore meteorologists and hydrologist must calibrate extracted data from these tools. In the Middle East countries such as the Khuzestan province of Iran, although the main source of climatic information is extracted meteorological skilled data from synoptic weather stations, the quantity and quality of these data may not be appropriate for several reasons. Occurrence of the Iran–Iraq war (1980–1988), shortage of skillful experts and suitable equipment, international sanctions and dust storms have reduced the quantity and quality of meteorological data. Therefore new techniques and tools can help meteorologists and hydrologist to analyse natural phenomena such as floods, droughts and occurrence of dust storm and calibration of extracted information from them is a necessary task.

Many researchers have studied different aspects of weather radar. Crisologo *et al.* (2014) used data from C-band weather radar in The Philippines and calibrated the data using 16 rain gauges in the 2012 wet season. They applied a fuzzy approach and specific differential phase and could estimate the daily rainfall to a satisfactory degree. Dung *et al.* (2016) used data from the DWSR-2500C Doppler weather radar in the Nha Be district, Ho Chi Minh City of Vietnam and observed that radar can forecast wind direction, wind velocity, and rainfall intensity in rainy days with high accuracy; Gou *et al.* (2018) developed two methods for determination of rainfall depth using radar in the Tibetan Plateau of China. They used data from 3,264 rainfall gauges and 11 Doppler weather radars in four precipitation events. The two applied methods were Reflectivity Threshold (RT) and Storm Cell Identification and Tracking (SCIT) algorithms. They showed that results from the SCIT method were more accurate than results from the RT method. Zhong *et al.* (2016) developed a Radar Supported Operational Real-time Quality Control (RS_ORQC) method for determination of hourly rainfall intensity and improved recorded hourly rainfall depth in rainfall gauges in eastern China. They used rainfall data from June, July and August 2010 and 2011. Results of this research showed that accuracy of recorded hourly data by rainfall gauges is more than 93%. Ye *et al.* (2013) used radar reflectivity data of six Doppler radar in the Huaihe River Basin of China and converted them to rainfall intensity for a heavy rainfall event in July 2007. They calibrated data collected by radar using measured data from rainfall gauges and observed that error in estimated rainfall intensity by radar networks is less than 45%. Josephine *et al.* (2014) used hourly data from Doppler weather radars and rainfall gauges to estimate runoff using the the Hydrologic Modeling System (HEC-HMS model). Their case study was Chennai basin, Tamil Nadu, India. They observed that difference between simulated volumes of two hydrographs is negligible, while difference between simulated peak discharges and time to peaks of two hydrographs is high (the sources of rainfall data of two simulated hydrographs are data from Doppler weather radar and rainfall gauges). Maity *et al.* (2015) applied a copula-based approach for determination of uncertainty of the transfer function Z–R (radar reflectivity (Z) and rainfall intensity (R)) in India and observed that this approach is a suitable tool for this purpose. Keblouti *et al.* (2015) used data from weather radar for simulation of runoff in Seybouse, Annaba watershed in north-eastern Algeria. Simulated runoff using data from weather radar was more accurate than simulated runoff of rainfall data from rainfall gauges. Lagrange *et al.* (2018) applied the wavelet-based scattering transform for classification of collected data by weather radar. These data concern the Nantes region of western France over 23 rainy days in 2009 and 2012. This method classified radar images well and its accuracy was 93.5%. Moreau *et al.* (2009) evaluated errors of 1-year data of Polari metric X-band radar in comparison with rainfall data from 25 rainfall gauges. They considered spatial variability of rainfall and used the ZPHI algorithm for processing rainfall data in real time. Their case study was the Beauce region (80 km south of Paris) in France. Accuracy of the applied algorithm was acceptable. Pedersen *et al.* (2010) utilized data from a Local Area Weather Radar (LAWR). It is X-band weather radar in Denmark. They concluded that increasing the number of calibrated parameters in the transfer function Z–R decreases uncertainty. Ahm & Rasmussen (2017) in the Aalborg of Denmark developed a transfer function Z–Q (flow discharge) instead of the transfer function Z–R and observed that performance of this transfer function is similar to the transfer function Z–R. Peleg *et al.* (2018) generated intensity–duration–frequency (IDF) curves using data from radar and Generalized Extreme Value (GEV) distribution in the eastern Mediterranean area of northern Israel during a 23-year period. They observed that subpixel variability of rainfall intensity increases with increase in return period and reduction of duration of rainfall. Villarini & Krajewski (2010) used data from the Weather Surveillance Radar-1988 Doppler (WSR-88D) in Oklahoma City, USA over a 6-year period. They evaluated uncertainty of three types of transfer function Z–R (Marshall–Palmer, default Next Generation Weather Radar (NEXRAD), and tropical). For this purpose they compared results of these transfer functions with recorded rainfall data from rainfall gauges. van de Beek *et al.* (2010) utilized data from 195 rainfall event that were prepared by the X-band weather radar SOLIDAR and rainfall gauges in Delft in the Netherlands from May 1993 to April 1994. They evaluated spatial and temporal resolution of this type of weather radars and concluded that they can be applied for rainfall monitoring in small watersheds. Ku *et al.* (2020) used data from dual-pol radar in Korea from 2014 to 2017. They considered six rainfall events and determined parameters of a radar rain rate estimator. They applied stochastic methods and derived parameters for severe rainfall events and showed that the peak rain rate is very important for determination of parameters. Kirsch *et al.* (2019) derived two transfer equations Z–R by data of three micro rain radars in the north of Germany. They illustrated that results of these transfer equations are more accurate than results of the Marshall–Palmer relation.

This research extracts the best transfer equation between Z and R in a watershed of the Khuzestan province, Iran. Accuracy of calibrated rainfall data by this transfer equation will be compared with accuracy of collected rainfall data from rainfall gauging stations. Therefore the HEC-HMS rainfall–runoff model produces flood hydrographs using these two types of rainfall data and compares these hydrographs with observed flood hydrographs.

The objectives of this research are as follows:

1. Determination of the optimum transfer function Z–R for the Abolabbas watershed. This relation should replace the Marshall–Palmer relation and suitable transfer function Z–R for the whole province of Khuzestan.
2. Verification of the extracted transfer function Z–R for the Abolabbas watershed by HEC-HMS rainfall–runoff model. For this purpose, simulated runoff according to generated rainfall data using this equation will be compared with simulated runoff according to rainfall data from rainfall gauges.

The new aspects of this research are as follows:

1. Extraction of the transfer function Z–R for a special watershed. This subject can increase precision of data of weather radar for simulation of rainfall–runoff. Because of occurrence of dust storms and similarity of size of dust particles and rain drops, this approach is necessary for this region.
2. The use of time intervals less than 1 hr for rainfall hyetographs (15 minutes). This use can improve results of rainfall–runoff model.
3. The Use of an optimization method for determination of the transfer function Z–R and considering seasonal characteristics of precipitation that can distinguish two transfer functions Z–R. These transfer functions Z–R concern seasons when rainfall is light to moderate rain or heavy to violent.

MATERIALS AND METHODS

The Abolabbas watershed

The Abolabbas watershed is in the east of the Khuzestan province (49°54′–50°5′E and 31°29′–31°44′N). The area and perimeter of this watershed are 283 km^2 and 87.4 km. The range of height of this region is between 691–3,283 m (average height is 1,885 m). The Abolabbas River is a branch of the Zard River. The Pole Manjenigh hydrometric station is at the end of the Abolabbas River (49°54′E, 31°31′N and height = 700 m). The slopes of the watershed and river are 20.54% and 6.46% respectively and length of the Abolabbas River is 38.08 km. The mean annual flow discharge, precipitation, evaporation and temperature of this watershed are 3.39 CMS, 584 mm, 2,700 mm and 21.6 °C respectively.

Figure 1 shows the location and map of this watershed. From February to May, heavy- to violent rains occur in this watershed and their source is convective precipitations as rain showers. In other months light to

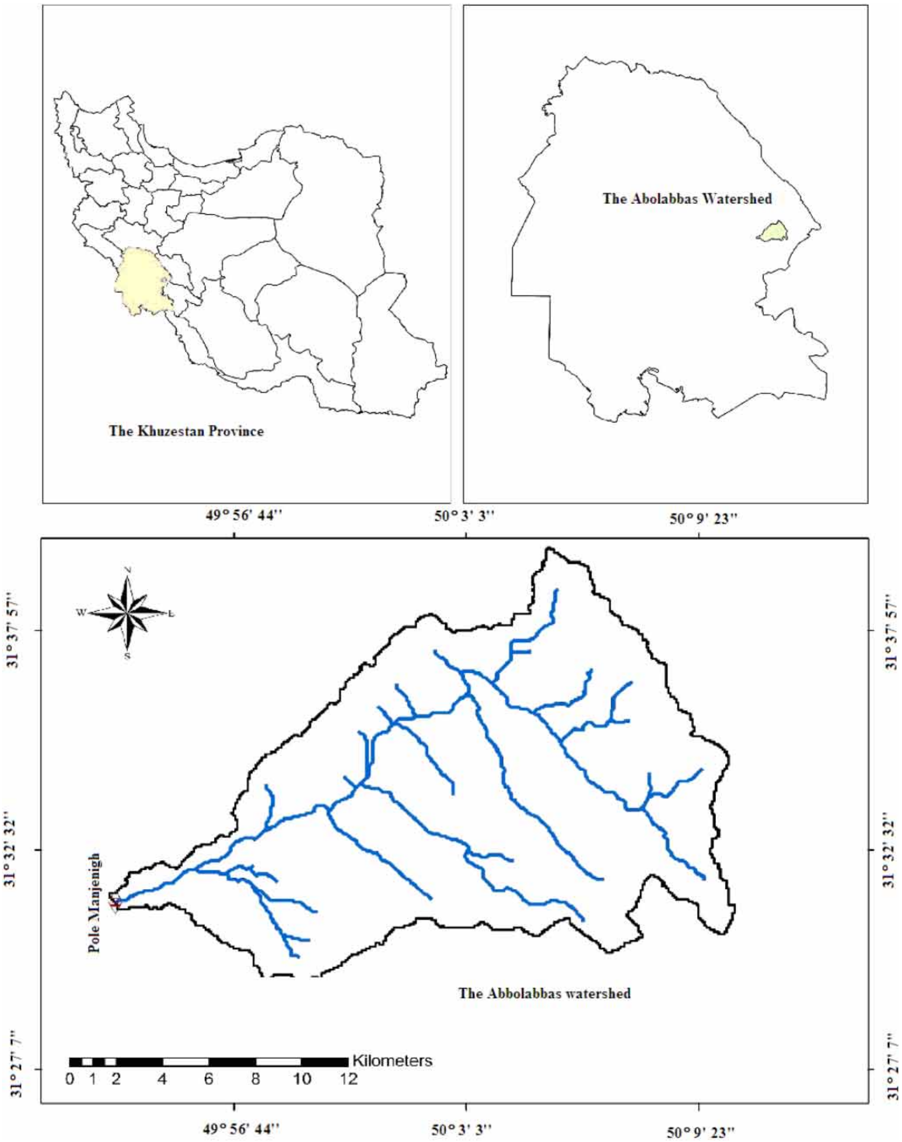

Figure 1 | The location and map of the Abolabbas watershed.

moderate rains occur in this watershed and their source is frontal precipitations.

The Khuzestan province has a weather radar in Am Altamir of Ahvaz (48°32′E and 31°14′N). Operational radius of this radar is 250 km. this radar is the first weather radar in Iran. It is suitable for rain showers and its model is a Metero 1,500 s (made in Germany). Power and height of the weather radar are 750 kilowatt and 24 m. Diameters of antenna and dome are 8.5 m and 11.65 m. Operational frequency of the weather radar is between 2.7 to 2.9 GHz. The sender model is 1,500 TXS and the digital signal processor model is Aspen DRX. The software used for the weather radar are Selex ES- Gematronik and Rainbow® 5. Vertical rotational angle is between −2° to 90°. Figure 2 shows the Am Altamir S-Band weather radar and its position relative to the Abolabbas watershed.

Research methodology

Research methodology of this research includes the following steps:

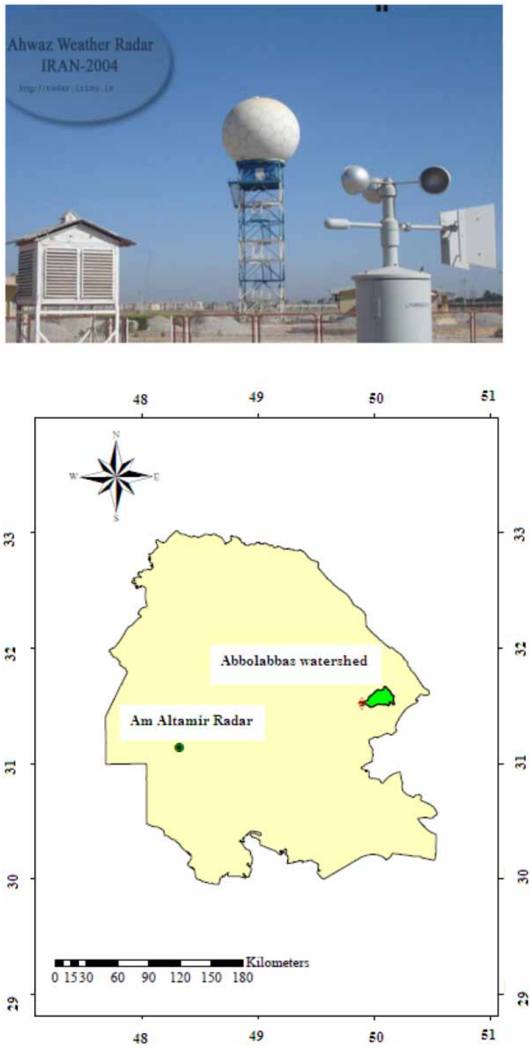

Figure 2 | The Am Altamir S-Band weather radar and its position relative to the Abolabbas watershed.

1 Selection of recorded rainfall gauging station for determination of the best transfer equation between the observed radar reflectivity (Z) and rainfall intensity (R) in the Abolabbas watershed. For this purpose, it selected the Bagmalek (49°52′E and 31°31′N) recorded rainfall gauging station. This synoptic weather station covers the whole watershed, also this station is close to the Pole Manjenigh hydrometric station.
2 Selection of appropriate rainfall hyetographs and their simultaneous flood hydrographs for calibration and validation of the HEC-HMS rainfall–runoff model. The rainfall and flow discharge data concern the Bagmalek rainfall gauging station and Pole Manjenigh hydrometric station respectively (daily data from 2007 to 2011). Time step of rainfall depth and flow discharge measurement is 15 minutes during the flood. It selected five flood hydrographs for calibration and two flood hydrographs for verification. The characteristics of these flood hydrographs are given (Table 1).
3 Extraction of the optimum transfer equation between Z and R. It utilizes observed rainfall hyetographs (with a 15 minute time step) from 2007 to 2011 (175 rainfalls). This research utilized 80% of collected data from weather radar for calibration of transfer equations and 20% of collected data from weather radar for verification of transfer equations.
4 Selection of suitable flood hydrographs for determining the accuracy of the extracted transfer equations. Therefore it selected two flood hydrographs with the listed characteristics (Table 2).

Figure 3 shows the flowchart of research methodology.

Table 1 | The characteristics of selected flood hydrographs for calibration and verification of HEC-HMS rainfall–runoff model

Date	C (calibration) or V (validation)	Rainfall depth (mm)	The peak discharge of flood hydrograph (CMS)	Rainfall duration (hr)	Peak time (hr)	Volume of stream flow (m^3)	Volume of base flow (m^3)
2007/12/13	C	20.9	16.1	5.5	6	477,900	172,080
2008/1/3	C	22.2	25.5	5.25	4	812,400	362,160
2009/3/18	C	46.8	67.4	5.5	6	1,248,500	236,880
2010/1/5	C	19.5	30.2	4.25	4	555,100	146,160
2011/3/12	C	20.3	33.2	5.5	4	699,800	235,440
2007/1/24	V	42.2	77.5	7.5	6	1,726,800	475,920
2011/4/23	V	24.1	26.3	4.5	6	1,034,600	652,320

Table 2 | The characteristics of selected flood hydrographs for verification of the extracted transfer equations

Date	Rainfall depth (mm)	The peak discharge of flood hydrograph (CMS)	Rainfall duration (hr)	Peak time (hr)	Volume of stream flow (m^3)	Volume of base flow (m^3)
2011/11/20	20.85	8	14	6	284,500	170,824
2011/2/25	19.3	5.7	22	6	364,800	227,160

Performance criteria

The used performance criteria are as follows.

Mean error (ME):

$$ME = \frac{1}{n}\sum_{i=1}^{n}(Q_{ci} - Q_{oi}) \quad (1)$$

where Q_c is calculated flow discharge (CMS), Q_c is observed flow discharge (CMS) and n is number of observations.

Mean absolute error (MAE):

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|(Q_{ci} - Q_{oi})| \quad (2)$$

Root mean square error (RMSE):

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Q_{ci} - Q_{oi})^2} \quad (3)$$

Mean bias error (MBE):

$$MBE = \frac{\sum_{i=1}^{n} Q_{ci}}{\sum_{i=1}^{n} Q_{oi}} \quad (4)$$

Normalized root mean square error (NRMSE):

$$NRMSE = \frac{RMSE}{\overline{Q}_o} \quad (5)$$

Correlation coefficient (R^2):

$$R^2 = \frac{\sum_{i=1}^{n}(Q_{ci} - \overline{Q}_c)(Q_{oi} - \overline{Q}_o)}{\sqrt{\sum_{i=1}^{n}(Q_{ci} - \overline{Q}_c)^2(Q_{oi} - \overline{Q}_o)^2}} \quad (6)$$

RMSE, NRMSE, MAE and ME values should be close to zero and MBE and R^2 should be close to one.

RESULTS

Calibration and validation of HEC-HMS rainfall–runoff model

Calibration of the HEC-HMS rainfall–runoff model determines different parameters for the model. This model used five flood hydrographs for calibration and two flood hydrographs for verification. This research utilized the Soil Conservation Service (SCS) method for calculation of infiltration and runoff volume, the peak time and peak discharge of flood hydrograph. Also it used the recession method for base flow separation and the Muskingum method for flood routing in the river. Figure 4 shows the curve number (CN) map of the watershed.

Calibrated parameters of the model for five flood hydrographs are given (Table 3).

In the verification stage, the value of parameters is the geometric mean of calibrated values of parameters using HEC-HMS.

The performance criteria values for different calibrated and verified flood hydrographs are given (Table 4).

The HEC-HMS rainfall–runoff model considers the peak discharge of flood hydrographs and volume of stream flow for calibration and verification of different flood hydrographs.

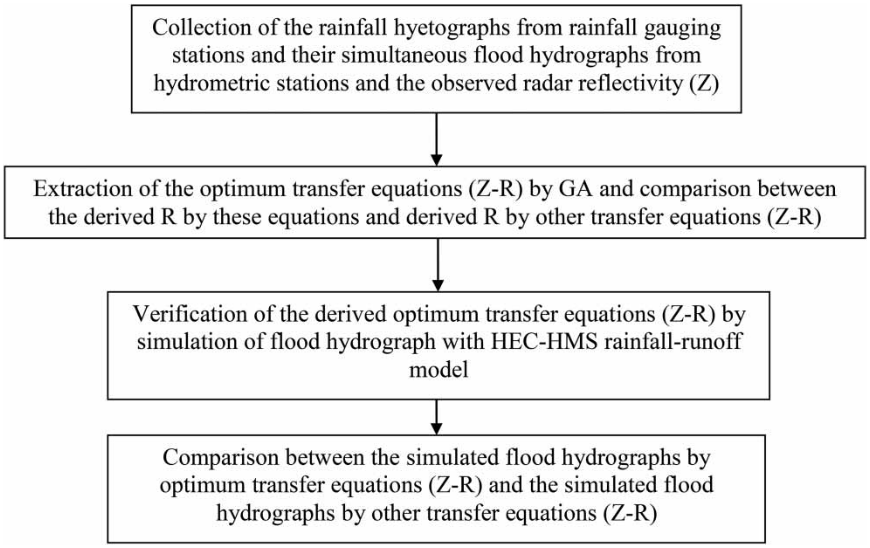

Figure 3 | The flowchart of research methodology in this study.

This model applied the Nelder–Mead optimization method for simultaneous optimization all parameters in this research. The model used Peak-Weighted Root Mean Square Error (PWRMSE) objective function and minimized this function:

$$\mathrm{PWRMSE} = \left\{\frac{1}{N}\left[\sum_{i=1}^{N}(Q_{pobs}(i) - Q_{pcal}(i))^2\left(\frac{Q_{pobs}(i) + \overline{Q_{pobs}}}{2\overline{Q_{pobs}}}\right)\right]\right\}^{0.5} \quad (7)$$

where Q_{pobs} is observed peak discharge of flood hydrograph and Q_{pcal} is calculated peak discharge of flood hydrograph.

Table 5 states the results of calibration and verification.

Figure 5 shows the observed rainfall hyetographs and the verified flood hydrographs.

Tables 4 and 5 and Figure 5 illustrate that calibrated values of model parameters are appropriate values for determination of the optimum transfer equations between Z and R.

Extraction of the optimum transfer equations between Z and R using of GA method

For finding the optimum transfer equations between Z and R, we prepared observed rainfall hyetographs (with 15 minutes time step) from 2007 to 2011 (175 rainfalls). The source of these data is a data set from the Iran Meteorological Organization. The form of this equation is $Z = aR^b$ (Seed *et al.* 2002) where (a) and (b) are constants that are affiliated to size and falling velocity of raindrops. Although this form of transfer equation is a conventional form, this research evaluated other forms of transfer equation but their RMSE was more than those of known form $Z = aR^b$. For example the RMSE of the optimum linear form ($Z = a + bR$) is 60% more than the RMSE of extracted optimum transfer functions in this research.

Most weather radar such as the Am Altamir S-Band weather radar use the Marshall & Palmer (1948) relation ($Z = 200R^{1.6}$). But using this relation may cause errors in the calculation of rainfall intensity. Therefore at each region a relation must be determined and this relation should consider climatic conditions. The GA method minimizes the RMSE value and determines the optimum transfer functions between Z and R. The GA method extracts optimum values for (a) and (b) and derived R by optimum transfer functions are compared with recorded rainfall intensity from rainfall gauging stations. The considered ranges of a and b are 30–500 and 1–5 respectively. The characteristics of applied GA in this research are:

Objective function = Minimize RMSE,

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(R_{obs} - R_{cal})^2} \quad (8)$$

where R_{obs} is observed rainfall intensity at the rainfall gauging station and R_{cal} is calculated rainfall intensity using the optimum transfer function.

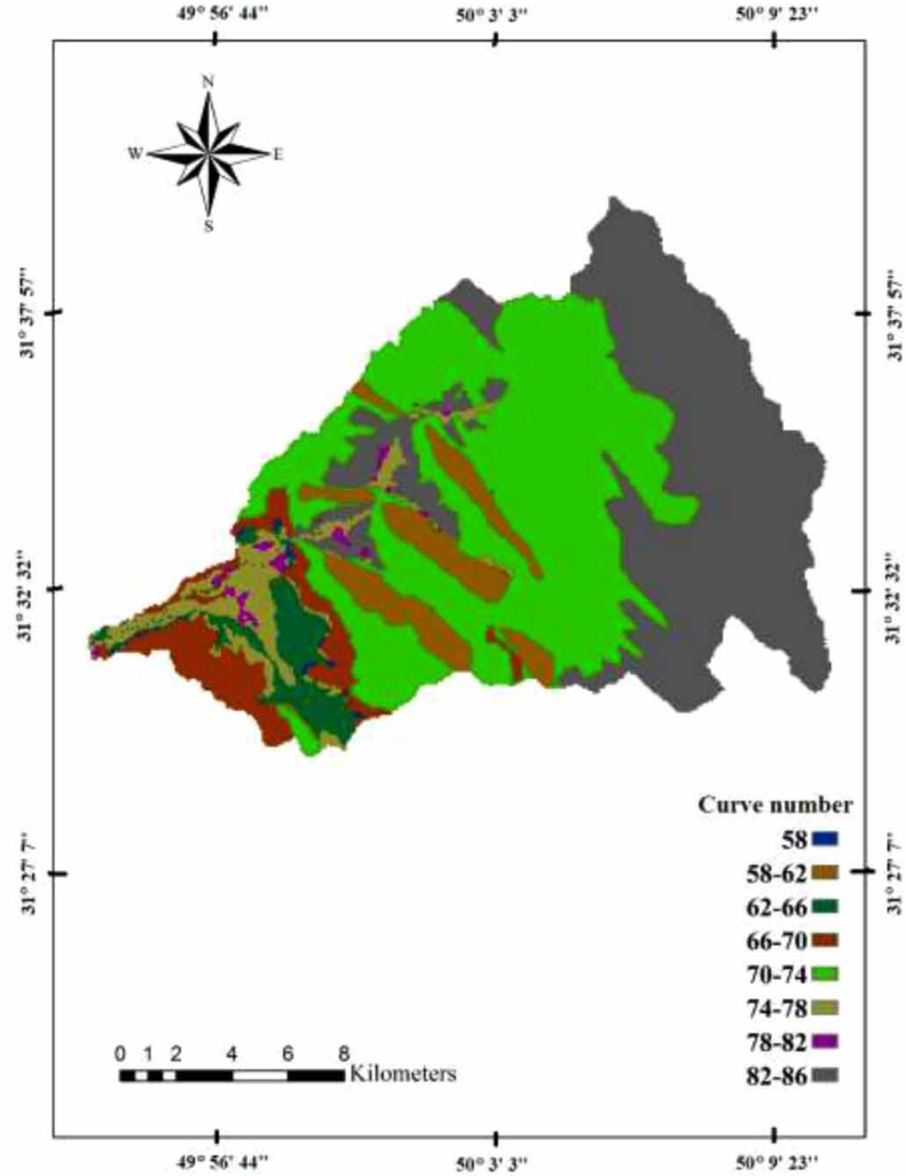

Figure 4 | The CN map of the Abolabbas watershed.

Rate of crossover = 0.8, Type of mutation = Uniform, Type of crossover = Heuristic, Selection method = Stochastic universal sampling, Number of generations = 3,000, Population of each generation = 120.

Applied GA in this research used a variable mutation rate for different generations. Mutation rates for different generations are:

Mutation rate = 0.3 if (no. of generation < 700)

Mutation rate = $(-0.295/1{,}300) \times$ (no. of generation -700) $+0.3$ if ($700 <$ no. of generation $< 2{,}000$)

Mutation rate = 0.005 if (no. of generation > 2000)

Figure 6 shows a sample of the RMSE changes in the calibration stage by GA.

GA method for improve results extracts two optimum transfer functions:

1. $Z = 110R^{1.8}$ (from February to May) for 38 rainfalls
2. $Z = 126R^{2}$ (for other months) for 137 rainfalls

From February to May, type of precipitation is convective rainfall as shower rains (heavy to violent rainfalls)

Table 3 | Calibrated parameters of HEC-HMS rainfall–runoff model

Parameter	Flood hydrograph (2007/12/13)	Flood hydrograph (2008/1/3)	Flood hydrograph (2009/3/18)	Flood hydrograph (2010/1/5)	Flood hydrograph (2011/3/12)	Geometric mean
Base flow to peak discharge of flood ratio	0.19	0.37	0.44	0.13	0.17	0.23
Base flow recession constant	0.71	0.48	0.47	0.21	0.45	0.43
CN	70.23	72.9	70.83	70.12	70.32	70.87
Initial abstraction (I_a) (mm)	16.49	13.24	13.52	9.81	12.2	12.87
K (hr) of Muskingum	0.39	0.11	0.1	0.66	0.1	0.2
X of Muskingum	0.19	0.4	0.2	0.47	0.1	0.23
Lag time (min)	121.11	120.76	90.1	120.34	94.65	108.46

Table 4 | Performance criteria values

Date	RMSE (CMS)	MAE (CMS)	ME (CMS)	MBE	NRMSE	R^2
2007/12/13	1.45	0.83	0.22	0.95	0.25	0.911
2008/1/3	1.73	1.06	0.38	0.96	0.18	0.94
2009/3/18	3.28	1.91	0.44	1.03	0.22	0.973
2010/1/5	2.06	1.27	0.76	0.9	0.31	0.938
2011/3/12	1.73	1.28	0.06	0.99	0.21	0.958
2007/1/24	3.32	2.12	1.18	0.95	0.16	0.988
2011/4/23	1.23	0.54	−0.05	1	0.1	0.959

while at other months the type of precipitation is frontal rainfall (light to moderate rainfalls). Type of rainfall can affect the observed radar reflectivity (Z).

Table 6 shows RMSE and R^2 of the Marshall–Palmer relation ($Z = 200R^{1.6}$), the optimum transfer equations ($Z = 110R^{1.8}$ and $Z = 126R^2$) and transfer equation for the Khuzestan province ($Z = 166R^2$) in calibration and verification stages. Iran Meteorological Organization advised that the transfer equation ($Z = 166R^2$) must be applied for calculation of the rainfall intensity in the Khuzestan province.

It should be noted that using an optimum transfer function alone increases RMSE and reduces R^2. The RMSE and R^2 for $Z = 110R^{1.8}$ alone are 0.92 mm/hr and 0.9 respectively and the RMSE and R^2 for $Z = 126R^2$ alone are 0.65 mm/hr and 0.93 respectively. Figure 7 shows the observed and calculated values of rainfall intensity by different equations at the verification stage; 80% of rainfall (observed 2007 to 2010) is used for calibration of GA and

Table 5 | The results of calibration and verification of different flood hydrographs

Date	The observed peak discharge of flood hydrograph (CMS)	The calculated peak discharge of flood hydrograph (CMS)	Percentage of difference between obs. and cal. (%)	The observed volume of stream flow (m^3)	The calculated volume of stream flow (m^3)	Percentage of difference between obs. and cal. (%)
2007/12/13	16.1	16.6	3.11	477,900	510,000	6.72
2008/1/3	25.5	24.5	−3.92	812,400	847,800	4.36
2009/3/18	67.4	67.2	−0.3	1,248,500	1,211,500	−2.96
2010/1/5	30.2	28.2	−6.62	555,100	621,700	12
2011/3/12	33.2	31.3	−5.72	699,800	708,900	1.3
2007/1/24	77.5	78.8	1.68	1,726,800	1,836,700	6.36
2011/4/23	26.3	26.9	2.28	1,034,600	1,024,900	−0.94

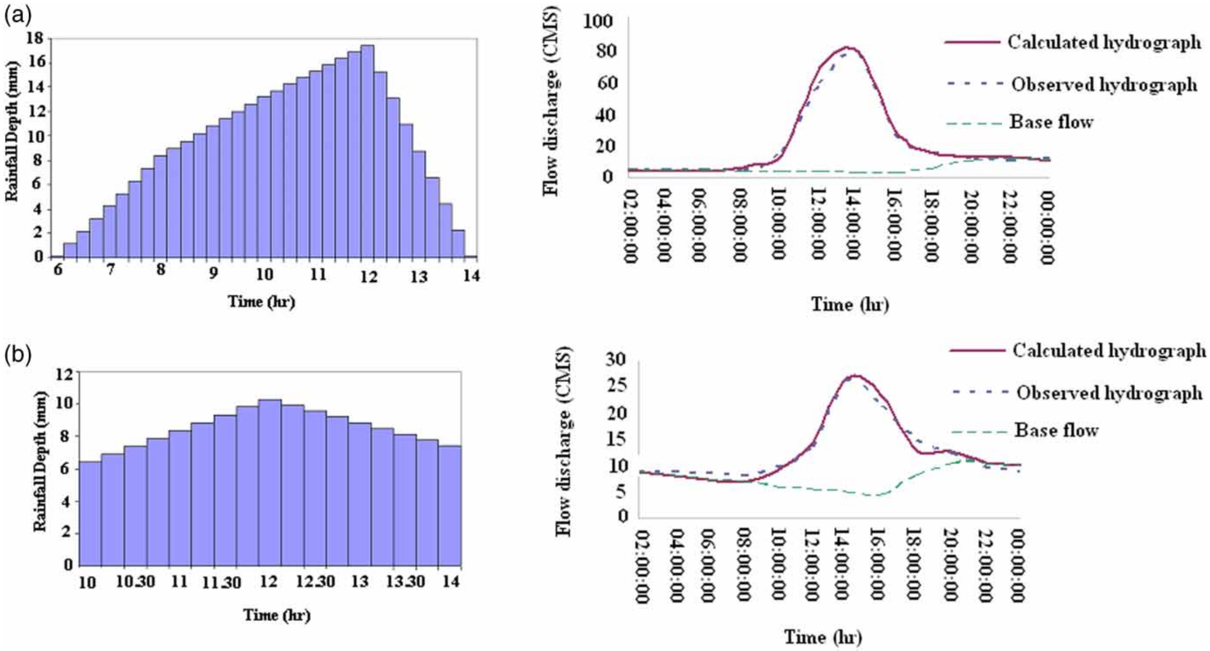

Figure 5 | The observed rainfall hyetographs and the verified flow hydrographs (a) 2007/1/24 (b) 2011/4/23.

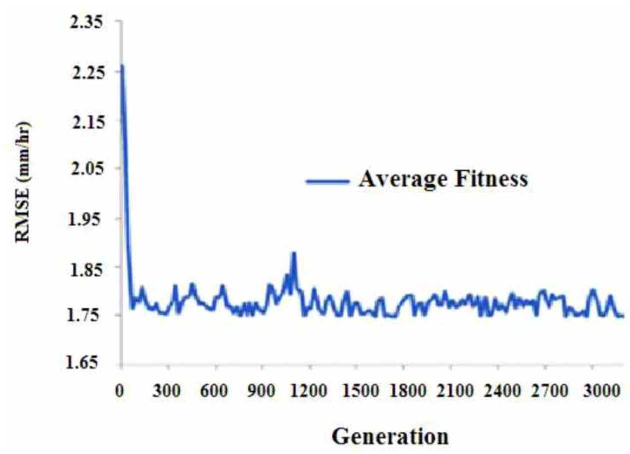

Figure 6 | A sample of the RMSE changes in calibration stage of GA.

extraction of optimum transfer functions and 20% of rainfall (observed in 2011) are used for verification of extracted optimum transfer functions.

Verification of accuracy of the extracted optimum transfer equations by calibrated HEC-HMS rainfall–runoff model

To be more confident of the optimum transfer equations, the calibrated HEC-HMS model used two rainfall hyetographs (prepared by measured rainfall depths in the Bagmalek rainfall gauging station) and their simultaneous flood hydrographs. In this stage, four types of rainfall data are introduced to HEC-HMS model:

(a) Collected rainfall data in the Bagmalek rainfall gauging station
(b) Extracted rainfall data from the Marshall–Palmer relation ($Z = 200R^{1.6}$)
(c) Extracted rainfall data from the optimum transfer equations ($Z = 110R^{1.8}$ and $Z = 126R^2$)
(d) Extracted rainfall data from transfer equation in the Khuzestan province ($Z = 166R^2$).

Figure 8 shows the observed and derived flood hydrographs using these rainfall data.

Figure 8 illustrates that the Marshall–Palmer relation ($Z = 200R^{1.6}$) is an unsuitable transfer equation for calculation of rainfall intensity using observed radar reflectivity. The simulated runoff volume and flood peak discharge by this transfer equation are much bigger than those of observed hydrographs. The transfer equation in the Khuzestan province ($Z = 166R^2$) is more accurate than the Marshall–Palmer relation. The simulated flood peak discharges of flood hydrographs using this transfer equation are very close to observed values. But the

Table 6 | The RMSE and R^2 of different transfer equations in calibration (C) and verification (V) stages

		$Z = 200R^{1.6}$		$Z = 166R^2$		$Z = 110R^{1.8}$ and $Z = 126R^2$	
Duration	**Performance criteria**	**C**	**V**	**C**	**V**	**C**	**V**
February to May	RMSE (mm/hr)	3.45	5.45	2.16	4.38	0.63	1.21
	R^2	0.53	0.82	0.54	0.84	0.96	0.99
Other months	RMSE (mm/hr)	2.62	2.19	2.46	1.95	0.55	0.5
	R^2	0.81	0.72	0.82	0.75	0.99	0.99

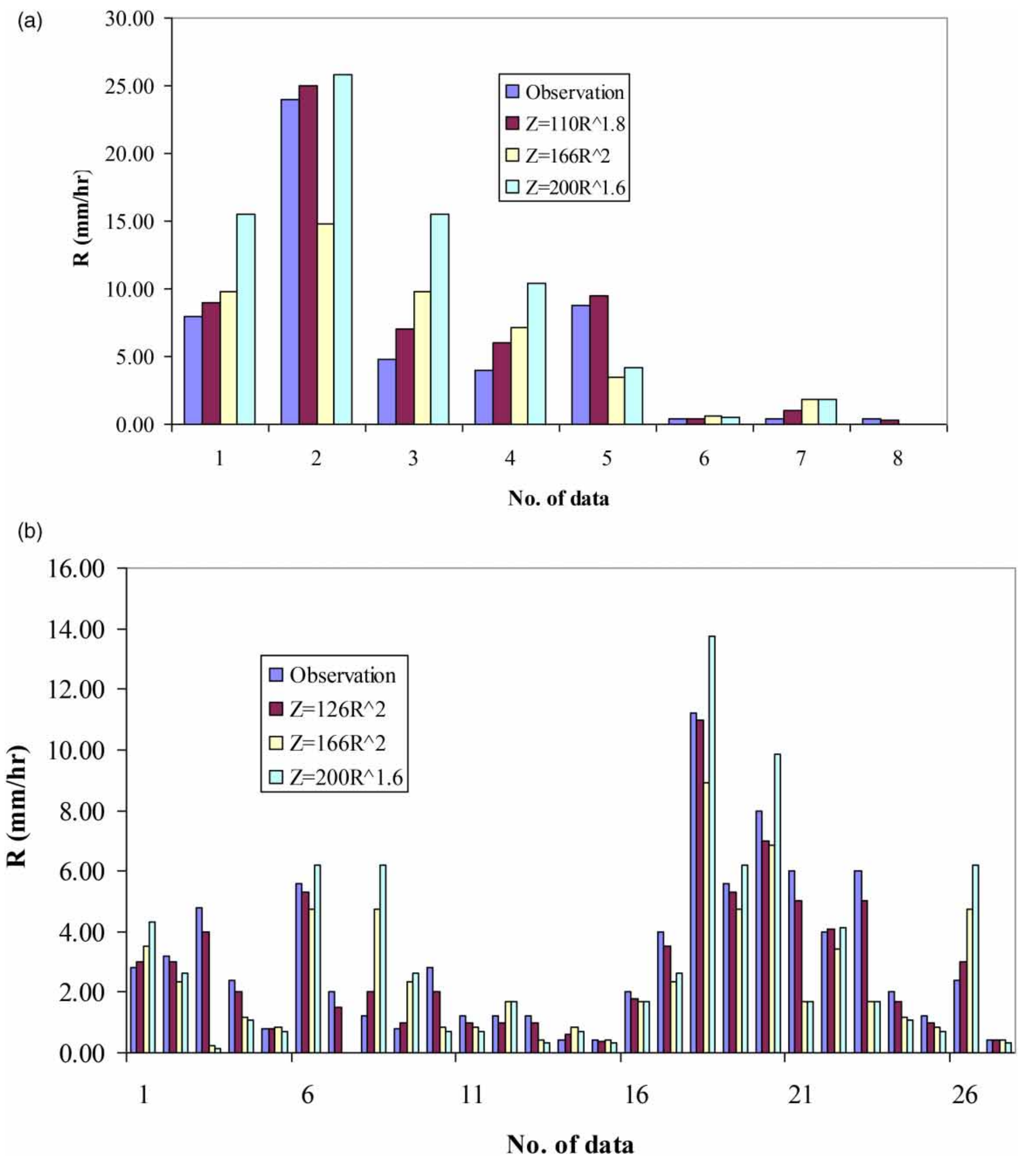

Figure 7 | The values of observed and calculated rainfall intensity in the verification stage. (a) February to May; (b) other months.

accuracy of the derived optimum transfer equations ($Z = 110R^{1.8}$ and $Z = 126R^2$) is more than the accuracy of the transfer equation ($Z = 166R^2$). Because the derived optimum transfer equations concern different periods of the year and they were derived for two types of precipitations, heavy to violent rainfall and light to moderate rainfall.

Performance criteria values for two flood hydrographs are given (Table 7).

Figure 8 and Table 7 show that the optimum transfer equations have the most fitness with observed data in comparison to other transfer equations. Therefore for each watershed, suitable transfer equations must be derived.

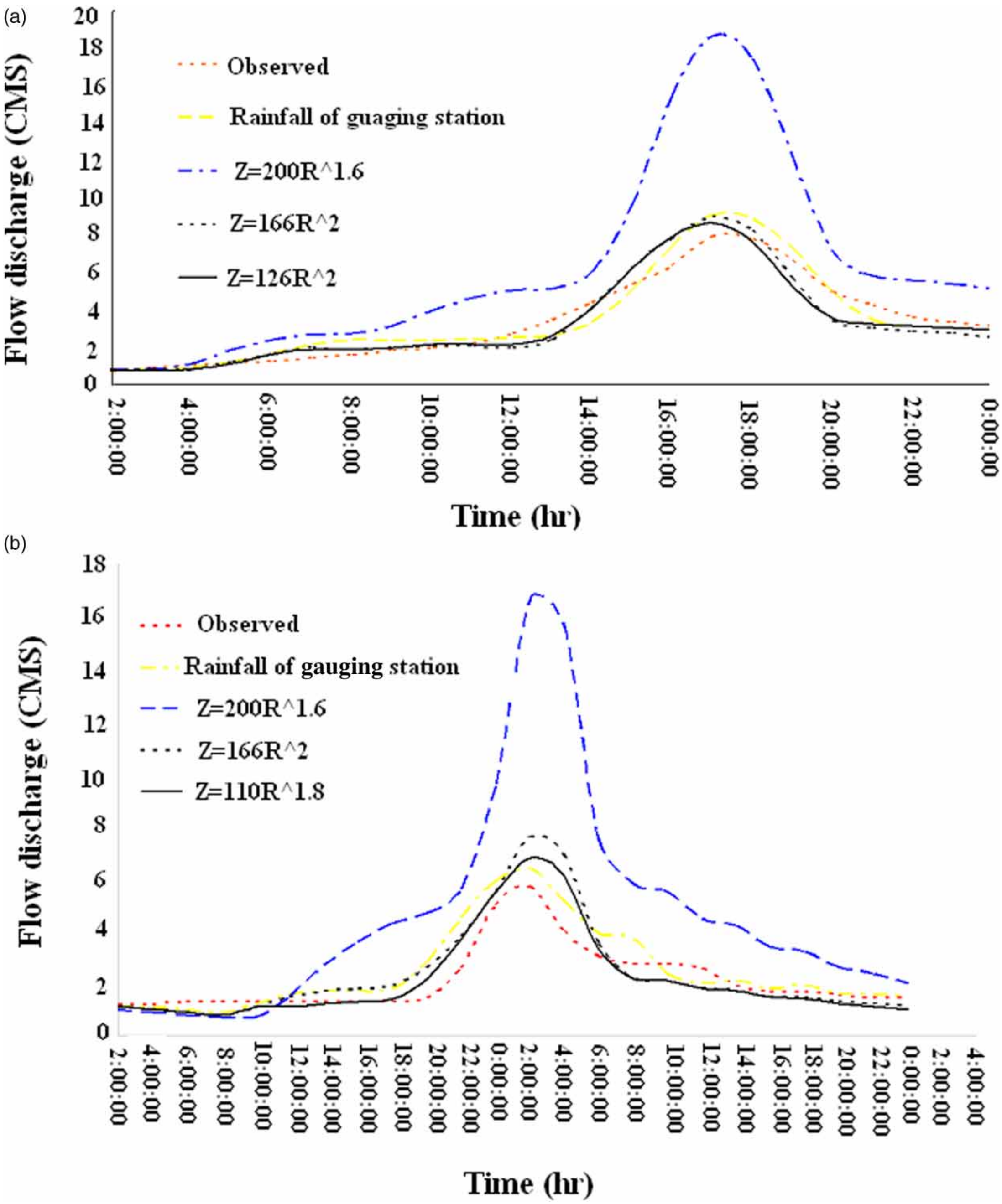

Figure 8 | The observed and derived flood hydrographs using introduced different rainfall data to HEC-HMS rainfall–runoff model (a) 2011/11/20 (b) 2011/2/25.

Table 7 | Performance criteria values for two flood hydrographs

Date	Source of rainfall data	ME (CMS)	MAE (CMS)	RMSE (CMS)	MBE	R^2
2011/11/20	Rainfall gauging station	0.11	0.46	0.58	0.97	0.94
	$Z = 200R^{1.6}$	2.59	2.59	3.92	0.56	0.9
	$Z = 166R^2$	−0.11	0.55	0.71	1.04	0.91
	$Z = 126R^2$	−0.09	0.98	0.66	1.03	0.92
2011/2/25	Rainfall gauging station	0.34	0.48	0.67	0.86	0.88
	$Z = 200R^{1.6}$	2.35	2.52	3.85	0.47	0.77
	$Z = 166R^2$	0.21	0.58	0.85	0.91	0.82
	$Z = 110R^{1.8}$	0.03	0.94	0.64	0.99	0.86

CONCLUSION

Determination of the optimum transfer equations between Z and R is a necessary task in different countries and watersheds. For this purpose, each region needs to a network of weather radars. Unfortunately, the number of weather radars is limited in developing countries. For example, the Khuzestan province (with area 64,055 km^2) has an weather radar. This weather radar cannot cover the entire province. Because of this reason the Abolabbas watershed (close to weather radar) was selected as the case study.

Using the Marshall–Palmer relation ($Z = 200R^{1.6}$) as the transfer function Z–R is a conventional approach for converting observed radar reflectivity (Z) to rainfall intensity (R) but this equation is not suitable for many regions of the world. Therefore this equation must be modified. In the Khuzestan province, the Khuzestan Water and Power Authority (KWPA) extracted a transfer function Z–R ($Z = 166R^2$) for this province. In simulation of runoff by HEC-HMS model, using this modified equation rather than using the Marshall–Palmer relation decreases RMSE up to 80% and increases R^2 up to 37%.

This research distinguished transfer functions Z–R for using the data from S-Band Doppler weather radar in the Abolabbas watershed by minimizing RMSE. For this purpose this research used the GA method and extracted two optimum transfer functions for convective and frontal rainfalls. Using the specific transfer function for each type of precipitation can improve simulation of runoff by rainfall–runoff models.

In simulation of runoff using the HEC-HMS model, adopting these optimum equations ($Z = 110R^{1.8}$ and $Z = 126R^2$) rather than using equation ($Z = 166R^2$) decreases RMSE up to 17% and increases R^2 up to 3%. Also in simulation of runoff using the HEC-HMS model, adopting equations ($Z = 110R^{1.8}$ and $Z = 126R^2$) is similar to using rainfall data from rainfall gauges and their RMSE and R^2 are almost equal. The volumes, peak discharges and times to peak of simulated flood hydrographs from this equation is similar to observed flood hydrographs. Results of other studies such as Josephine *et al.* (2014), Keblouti *et al.* (2015) and Seed *et al.* (2002) showed appropriate accuracy for using data from weather radars for simulation of rainfall–runoff events and their results confirmed the obtained findings of this research.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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