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The effects of forecasted precipitation amount on probable maximum precipitation and probable maximum flood parameters

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Abstract

This study aims to calculate the probable maximum precipitation (PMP) and probable maximum flood (PMF)parameters. For this purpose, data length adequacy of historical precipitation data and data forecasted were analysed using the Long Ashton Research Station Weather Generator under Representative concentration pathway 8.5 and 4.5 scenarios in 2021-2040. Modified method and the method provided by soil conservation service-curve number were used to estimate (PMP) and (PMF)parameters, respectively. To investigate data adequacy, the Hurst coefficient was examined for Shiraz, Abadeh and Lar according to the length of statistical periods. Shiraz, Abadeh and Lar have the desired data with the coefficients of Hurst 0.61, 0.57 and 0.52, respectively. The results indicate increased precipitation under both Representative concentration pathway 4.5 and 8.5 scenarios in 2021-2040 for all three climate zones compared to historical data. (PMP) parameter has experienced an increasing trend in Abadeh and Lar and a decreasing trend in Shiraz due to a decrease in the value of 24hour (PMP) parameter under both scenarios compared to historical data. Given the (PMP) parameters for Shiraz region, the (PMF)parameter has experienced a downward trend under both scenarios and an upward trend for Lar and Abadeh compared to historical data.

Keywords

Hershfield Model; Long Ashton Research Station Weather Generator (LARS-WG); Precipitation forecast; Probable maximum flood (PMF); Probable maximum precipitation (PMP).

Introduction

Flooding is an excessive increase in the volume of water during or after extreme precipitation[1]. When a flood event occurs, after an increase in the water volume, the river flow increases rapidly and the water level rises as well. As a result, the water overflows from its normal path and dominates the surrounding areas in the form of flooding[2]. Floods are among the most common natural disasters[3]. The magnitude of the floods and their recurrence over time depend on precipitation intensity, land infiltration, and regional topography. The probability of occurrence and magnitude of future floods in the region can be determined by studying old floods and their alluvium [4]. In Iran, the risk of flooding is very high such that they lead to increased financial and human losses. According to studies, about 40 large and small floods occur annually across the country, leading to extensive damage to the economy. Flood risk management has become a dominant approach in much of the world for addressing the potential consequences due to flooding events. It is, in fact, a vast improvement from traditional measures which had prevailed previously. Traditional methods can be characterized by structures built in an attempt to control rivers, largely ignoring vulnerability[5] .Therefore, identifying the factors contributing to such damages and events is considered vital in finding several strategies to reduce their effects [6]. Planning and designing hydraulic structures often require assessing the potential for precipitation and flooding in drainage basins. As a result, design requirements must be estimated based on the concept of regional probable maximum flood (PMF)[7]. To prevent flood damage, the concept of PMF should be used to design high-risk projects regarding hydraulic considerations[8]. Many meteorological variables affect the intensity of PMF. One of the most important variables is the probable maximum precipitation (PMP), which considers the most probable precipitation. Soil moisture, snowfall, temperature sequence, reservoir capacity, etc. can also affect the value of PMP in runoff and increase the probability of a large flood [9].Statistical approaches such as Hershfield can be used to calculate PMP. To calculate the PMP, Hershfield applied a constant value of 15 multiplied by the standard deviation of the statistical period plus mean annual precipitation in his initial method. He then stated that the frequency coefficient should not be a constant value of 15, and rather should be different from the precipitation duration. He found that 15 was too high for wet watersheds (i.e., extreme precipitation) and less than 24 hours for precipitation duration. Hence, Hershfield prepared a diagram showing the variables of the frequency factor between 5 and 20, depending on the average value of annual maximum precipitation and precipitation duration [7]. The 21st century is witnessing many environmental problems, with climate change becoming one of the most important. Since different societies pay more attention to rapid industrial development and less to the environment, the negative effects of climate change can be more severe in the future. An increase in this probability in future periods could have devastating effects on human societies. Thus, research on this series of topics, including flooding for various watersheds, has been recently taken into consideration worldwide[10] The LARS-WG model is one of the most popular stochastic weather data generators applied to produce minimum and maximum temperatures, precipitation, and daily radiation under current and future climatic conditions. Compared to other programs, the LARS-WG model is more widely used because of its repetitive calculations, less need for input data, simplicity, and high efficiency. This model was introduced many years ago by Racsko et al., (1991) and then revised by Semenov et al. In Canada[11]. Clavet-Gaumont et al., (2018) estimated the PMP and then the PMF By simulating climate models, they concluded that PMF might increase by up to 20%. Watershed management requires runoff information to protect and develop natural resources[9]. Spatial data provide accurate forecasting of runoff with hydrological applications as well[12]. Miguel et al., 2014 Estimated the PMP and PMF. They stated temperature projections would also affect the maximization factors in the calculation of the PMP, as precipitable water content (PWC), raising it to 126.6% and 62.5% under scenarios A2 and B1 (Respectively, for the period 2045 – 2065), respectively; the PMF would increase to +175.5% under the A2 scenario[13]. There are many ways to model rainwater runoff. The curve number method (SCS-CN, 1972) is a widely used adjustable method for runoff estimation[14]Moreover, Tailor and Shrimali., (2016) simulated the runoff pattern and volume of the Ropen Khan watershed in India using the SCS-CN method along with remote sensing and Geographic information system (GIS) [15].In Thailand, a study was conducted to assess the safety of dam spillway. In this study, to evaluate the hydrological safety dimensions of the dam, PMP was analyzed using the Hershfield statistical method, which led to the assurance of dam safety [16].Chen et al., 2013 considered forecasting climate change using the

LARS-WG model. This researcher predicted that precipitation would experience an upward trend in most seasons in South Sudan from 2011 to2030 [17].This study was conducted in 2020.02.08 with the aim of calculating the maximum rainfall and the maximum possible flood parameters in Fars province and the three cities of Shiraz, Abadeh and Lar.

2. Materials and Methods

2.1. Study area

With an area of about 1226.8 Square kilometre (km^2), Fars Province makes up about 6.7% of Iran's area. This province is located in the south of the central region of Iran between 2°27′ - 31°42′ N and 50°42′ -55°36′ E. It is adjacent to Hormozgan Province from the south, Kohgiluyeh va Boyer-Ahmad and Bushehr provinces from the west, Isfahan and Yazd provinces from the north, and Kerman Province from the east. It has three climate zones with an altitude of 1540 metres above sea level (MASL) climatically, the province has three regions, i.e., temperate, cold, and hot. The cities studied in this study are "Shiraz" with a temperate climate zone, "Abadeh" with a cold climate zone, and "Lar" with a hot climate zone, located in Fars Province (Fig. 1). Table 1 shows the geographic information related to each of these three cities.

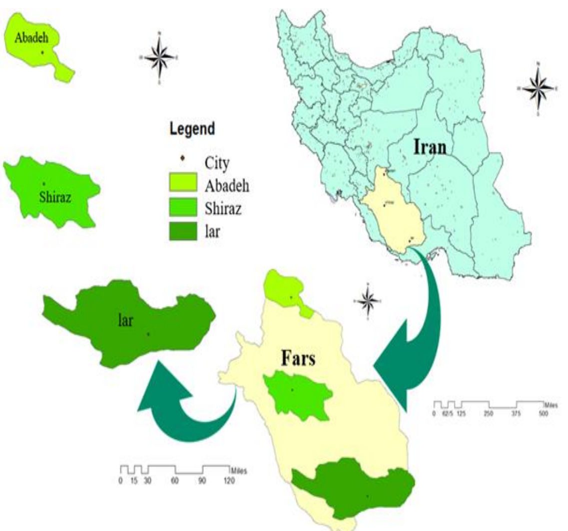

Figure 1. Geographic location of the study area in Fars Province along with showing the three location of Shirz, Abadeh and Lar cities

Table 1: Geographical information he cities under the current study

City Name	Climate Zone	Altitude	Longitude	Latitude
Shiraz	Temperate	1484	52-36-10	29-32-39
Abadeh	Cold	2030	52-36-42	31-11-54
Lar	Hot	792	54-22-29	27-40-12

The effects of climate change depend on the geographical conditions of the region. Therefore, climate change is evaluated on a local scale to allow for accurate forecasts[18]. The LARS-WG model is regarded among the best forecasting models for climate change parameters, including daily precipitation for areas with different climatic conditions[19]. LARS-WG is utilized as the spell-length approach, and it can be used for the simulation of weather data at a single site under current and future climate conditions. The data utilized in the form of daily time series for suitable climate variables are precipitation (in millimetre), maximum and minimum temperature (in Celsius), and solar radiation (in mega joule per square meter per day) [20].The results of previous research on climate forecasts using the LARS-WG model confirm the success of this model in forecasting meteorological parameters [21][22].Thus, to calculate the PMP and PMF parameters following the data adequacy test, this study used LARS-WG forecasted precipitation data under both Representative concentration pathway (RCP)8.5 and RCP4.5 scenarios in 2021-2040.

2.2. Data length adequacy

Data length adequacy is considered as one of the important factors in forecasting climate parameters and statistical studies that improve research validity. One of the best ways to check data length adequacy is the Hurst coefficient test. A Hurst coefficient greater than 0.5 indicates a desirable long-term memory in a longer time series. Eq. 1 shows the Hurst coefficient [23]

$$H = \frac{log\left(\frac{R}{Sx}\right)}{log\left(\frac{N}{2}\right)} \qquad \textbf{(1)}$$

Where, N is the amount of information per time series and Sx is the deviation of the time series criterion. Also, R is equal to the difference between the positive and negative values of the deviation from the “average time series”, calculated cumulatively using Eq. 2 [23]

$$R=s^{+} - s^{-} \quad (2)$$

Following the investigation of the data length adequacy for the studied cities, the precipitation parameter of the LARS-WG model was studied under both RCP4 and RCP8.5 scenarios in 2021-2040. Forecasted mean monthly precipitation (or average monthly rainfall) was compared with historical data and used to estimate the PMP parameter.

Probable maximum precipitation

Hershfield’s method is among the most widely used statistical method for calculating PMP. The Hershfield’ original equation is based on the Chow equation using Eq. 3[24].

$$\mathrm{PMP} = \bar{x}_n + k_n\sigma \quad (3)$$

Where, $\bar{x}_n$ is the mean annual maximum precipitation, σ is the standard deviation of a series of n annual maximum rainfall, and k_n is a function of the period of precipitation and mean annual series, a digit between 15 and 20. Reviews in Hershfield’s original method only made a series of changes to obtain the k_n parameter. Eq. 4 adjusts the k_n so that Hershfield modified method can be based on it[25].

$$k_n = \frac{x_1 - X_{n-1}}{\sigma_{-1}} \quad (4)$$

Where, x_1 is the observed 24-h PMP, X_{n-1} is the mean annual maximum except x_1, and σ_{-1} is the deviation from the annual maximum criterion except for the maximum value. The PMP values obtained are one of the most influential parameters for calculating PMF.

Probable maximum flood using the SCS-CN method

The approach used by the SCS-CN method is based on water balance. The general equation for the SCS-CN method is specified in Eq. 5[12].

$$Q = \frac{(P-Ia)^2}{(P-Ia)+S} \quad (5)$$

Where, Q is the total runoff depth, P is the calculated precipitation depth (PMP), S is the potential retention of rainfall, and Ia is the initial precipitation loss including interception and infiltration. Despite the initial precipitation loss of about 30%, the accumulation potential is assumed to be equal to 0.2 s, leading to Eq. 6[26].

$$Q = \frac{(P-0/2s)^2}{(P+0/8s)} \quad (6)$$

Furthermore, the parameter S is obtained from Eq. 7[27].

$$s = \frac{2540}{CN} - 25.4 \quad (7)$$

To estimate the curve number (CN), the land-use map and the hydrologic soil group map were combined in the GIS environment. As a result, several maps with smaller units were obtained, each with a specific hydrologic group with a specific use. Subsequently, the amount of CN was determined under moderate humidity conditions using CN tables for different types of land use in the basins according to hydrologic soil groups. Then, the weighted CN of each basin was calculated according to Eq. 8[14].

$$CN = \frac{\sum C_{N_i} A_i}{A} \quad (8)$$

Where, CN is the weighted average runoff curve number for the watershed, A_i is the area of each unit, C_{N_i} is the CN of each unit, and A is the total area of the entire region.

3. RESULTS AND DISCUSSION

To investigate data adequacy, the Hurst coefficient was examined for Shiraz, Abadeh, and Lar according to the length of statistical periods. The obtained Hurst coefficients are presented in Table 2.

TABLE 2: DATA ADEQUACY TEST (HURST COEFFICIENT)

CITY	Statistical period length	Hurst coefficient (H)
SHIRAZ	52	0.61
ABADEH	42	0.57
LAR	30	0.52

According to Table 2, Hurst coefficients obtained for Shiraz, Abadeh, and Lar indicate a desirable data length in a longer time series. Because of the adequate data length, the LARS-WG precipitation forecasts were examined under both RCP4.5 and RCP8.5 scenarios. The output parameters of the LARS-WG model were compared under both scenarios with historical data for each city. The comparison results of mean monthly precipitation are presented under both scenarios in the form of 2 Graphs Besides (Fig. 2).

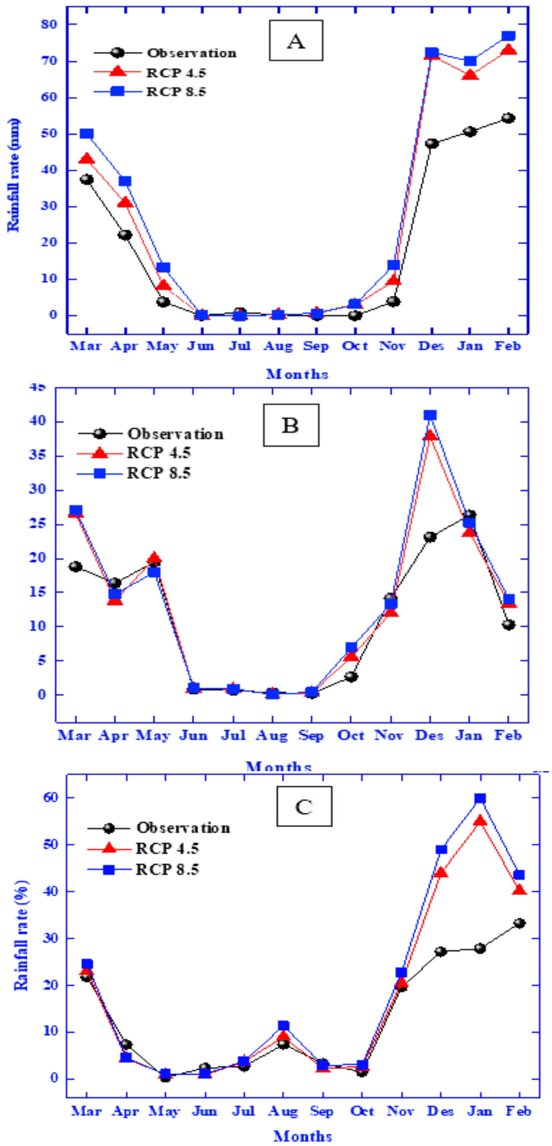

Figure 2: A comparison between monthly mean historical rainfall and RCP4.5 and RCP8.5 scenarios (A=Shiraz, b=Abadeh, and C=Lar)

According to Fig. 2, precipitation forecasting indicates an increase in the precipitation rate under different scenarios in Shiraz in all months except July under RCP4.5 and RCP8.5 and June under RCP4.5. It also shows an increase in precipitation in Abadeh in all months except April, August, November, and January under both scenarios and May under RCP8.5. As can be seen, precipitation rate increases in Lar in all months except April, June, and September. Overall, the forecasted mean annual precipitation in 2021-2040 indicates an increase in the precipitation rate that can have a large impact on the PMP parameter. To estimate this parameter, the modified Hershfield statistical method was used. Additionally, to perform calculations with high accuracy and speed for Shiraz, Abadeh, and Lar, a MATLAB code was written for this equation according to the available statistics. Table 3 shows the results of the comparison between the influential values/PMP parameter values and historical data/forecasted precipitation data of the LARS-WG model under both RCP4.5 and RCP8.5 scenarios.

Table 3: Comparison of PMP calculation parameters

Basin	Scenario	$\bar{x}_n$	σ	k_n	x_1	PMP with LARS-WG Model Data
Shiraz	Historical	43.13	15.41	4.28	99	109.1
	RCP4.5	60.96	17.7	2.07	93.4	97.64
	RCP8.5	60.9	17.52	1.98	92	95.81
Abadeh	Historical	29.81	16.17	3.95	83	93.78
	RCP4.5	34.6	19.75	3.5	87.2	103.9
	RCP8.5	37.32	20.74	3.4	92.1	107.95
Lar	Historical	38.36	22.41	2.67	91.5	98.28
	RCP4.5	63.6	32.3	2.3	128	138
	RCP8.5	70.7	36	2.32	142.6	142.5

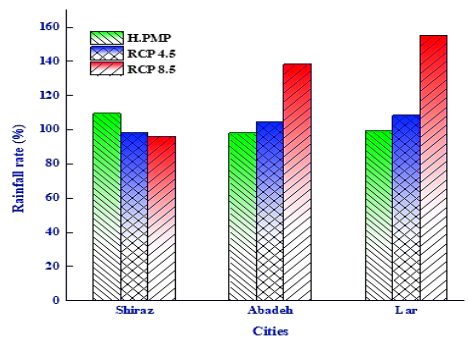

Figure 3: A comparison between historical PMP and scenario-based forecasting

The PMP values were calculated for historical data and forecasted data under both scenarios. According to the results, the PMP parameter has experienced an increasing trend in Lar and Abadeh. Furthermore, a decrease was observed in the PMP parameter due to the reduced parameter 24-h PMP (x1) compared to the historical data under both scenarios. PMF was calculated using the SCS-CN method for the studied cities, based on the estimated PMP data with historical data and the weighted CN values estimated by the GIS software (Fig. 4). Table 4 shows the output values of the weighted CN of the GIS software.

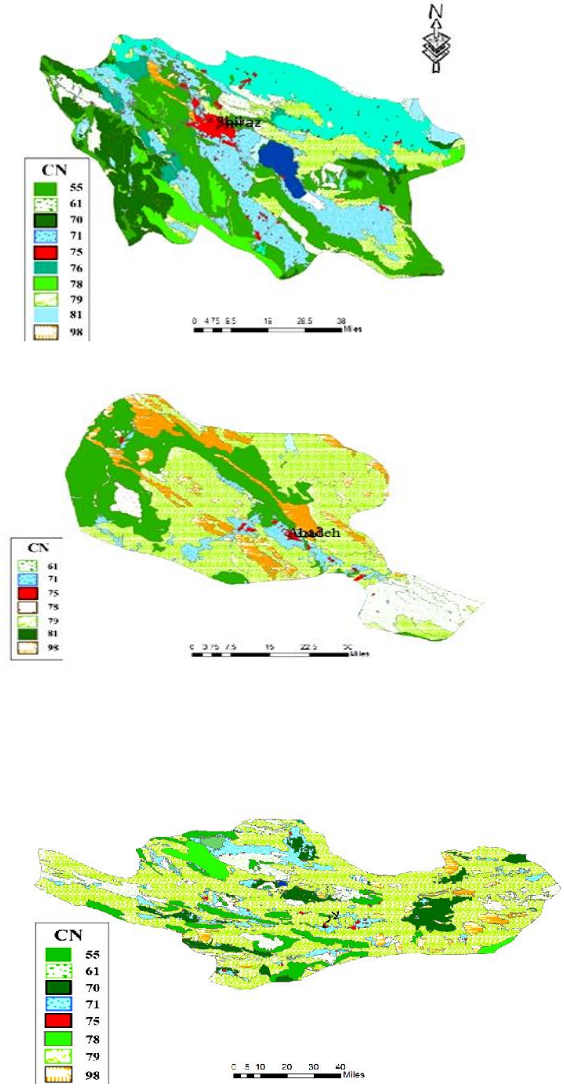

Figure 4: The curve number method map of Shiraz, Abadeh, and Lar

Table 4: CN, S, and PMF values (mm)

City	CN	S	PMF.H	RCP4.5	RCP8.5
Shiraz	79.45	6.57	101	90.2	88.34
Abadeh	76.3	7.88	85	95	99
Lar	77.1	7.54	89.7	129	133.8

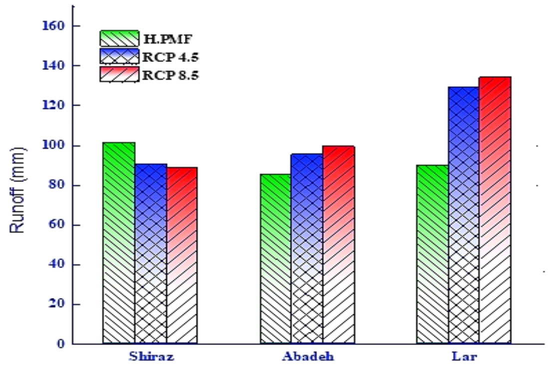

Figure 5: A comparison between historical PMF and scenario-based forecasting

PMP and CN are considered as two influential parameters in estimating the PMF parameter. According to the results presented in Table 4, an increase is observed in the PMF parameter in Shiraz compared to other cities in historical data due to the increased PMP parameter and CN coefficient. Likewise, according to forecasted precipitation under both RCP4.5 and RCP8.5 scenarios, a decrease was observed in PMF in Shiraz due to a decrease in PMP values compared to historical data and an increase in PMF in Lar and Abadeh due to an increase in the PMP parameter.

CONCLUSION:

Using historical data as well as GIS and LARS-WG models, an approach to predicting future PMPs and PMFs under changing weather conditions for the three cities of Abadeh, Shiraz and Lar from three different climatic zones in Fars province was created. The LARS-WG model uses the data observed to fit the daily distribution parameters of the variables for precipitation and performs dry and wet analysis separately. Hurst coefficients obtained for Shiraz, Abadeh, and Lar indicate a desirable data length in a longer time series. Because of the adequate data length, the LARS-WG precipitation forecasts were examined under both RCP4.5 and RCP8.5 scenarios. It also includes a mechanism for producing daily rainfall in weather information. The daily rainfall parameter with the LARS-WG model in the period 2021-2040 was obtained under two scenarios, RCP4.5 and RCP8.5, and the results show an increase in rainfall, especially in spring, in the three cities studied In both scenarios RCP4.5 and RCP8.5. The rate of PMFs was estimated using the SCS-CN method, and the changes predicted in PMFs will increase the CN coefficient due to the increasing development of urban areas as well as the reduction of agricultural and forestry lands. Which has increased the rate (PMF) and this increase could pose risks to the province.

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