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Antecedent Rainfall Thresholds for the Triggering of Deep-Seated Landslides (Case study: Chaharmahal & Bakhtiari Province, Iran)

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ABSTRACT Rainfall is recognized as one of the main triggering factors of landslides. Researchers have long attempted to determine the amount of precipitation required to trigger slope failures. One of the landslide zones in Iran is Chaharmahal & Bakhtiari province where many landslides cause high casualties in recent decades. It is significant that most of these landslides occur after a rainy period. Thus, determination of rainfall thresholds in this province seems to be necessary as the first step to present an effective landslide warning system. In this research, we tried to introduce some antecedent rainfall thresholds for deep-seated landslides. The antecedent periods considered for the events examined in this study were 5, 10, 15, 20, 25, 28 and 30 days. Since most of landslides occurred by cumulative rainfall for more than 10 days, the results of 5 days and shorter time periods appear not logically connected. We have also established rainfall thresholds for the 15-day antecedent period and 2, 3 and 5 days rainfall events. Results indicate that for 10 to 30 days antecedent periods, mean total rainfall needed to induce landslides varies between about 140 and 280 mm. Finally, we recommend more research on relation between rainfall characteristics and destabilization of different soil classes in the study area (especially clayey-marly deposits).

Key words: *Antecedent rainfall, Chaharmahal & Bakhtiari, Landslide, Threshold*

1 INTRODUCTION

Landslides constitute one of the major geohazards that cause substantial damage to property and loss of life every year across the globe. It is well known that rainfall is the most important and frequent trigger of landslides (Cannon and Ellen, 1985; Crozier, 1999; Jakob and Weatherly, 2003; Giannecchini, 2006, Sengupta *et al.*, 2010). Commonly, rainfall contributes to the triggering of landslides by the mean of water infiltration into the slope mantle, which causes an increase in pore pressure value and thus, decrease in soil shear strength. A threshold is the minimum or maximum level of some quantity needed for a process to take place or a state to change (White *et al.*, 1996).

For rainfall-induced landslides, a threshold may define the amount of rainfall that, when reached or exceeded, is likely to trigger landslides (*e.g.* Guzzetti *et al.*, 2007).

Rainfall thresholds can be defined on physical (Talebi *et al.*, 2008) or empirical bases

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(*e.g.* Campbell, 1975, Lumb, 1975; Canuti *et al.*, 1985; Corominas and Moya, 1999; Crosta and Frattini, 2001; Gabet *et al.*, 2004; Giannecchini, 2006; Dahal and Hasegawa, 2008). Review of the literature (*e.g.* Van Asch *et al.*, 1999; Corominas and Moya, 1999; Aleotti, 2004; Zezere *et al.*, 2005; Sidle, 2006) reveals that shallow failures are usually triggered by short intense storms, while more deeply-seated landslides are affected by longer term rainfall periods. It shows that there are no critical rainfall conditions for every type of landslide. However, determination of rainfall thresholds in the landslide-prone areas could be the basis for landslide warning systems (*e.g.* Aleotti, 2004).

Laprade *et al.* (2000) classified deep-seated landslides as those with movements to a depth greater than about two or three meters. On the other hand, many authors (such as Terlien, 1998; Van Asch *et al.*, 1999; Zezere *et al.*, 2005) considered two meters as maximum depth for shallow landslides. Thus we use a minimum depth of 2 m to distinguish more deeply-seated landslides from shallow landslides.

When using antecedent rainfall measurements to predict landslide occurrence, a key difficulty is the definition of the period over which to accumulate the precipitation. Kim *et al.* (1991) considered 3 days, Crozier (1999) and Glade *et al.* (2000) considered 10 days, Chleborad (2003) used 18 days (3-day event rainfall and 15-day antecedent rainfall), and Aleotti (2004) considered 7-, 10- and 15-day periods. Terlien (1998) tested 2-, 5-, 15- and 25-day periods and found best results for the longest rainfall periods. As expressed by Guzzetti *et al*. (2007) for antecedent rainfall in the range between 1 and 19 days before the landslide event in southern Italy, De Vita (2000) established that the daily rainfall needed to trigger landslides decreased with the amount of the antecedent rainfall; and if longer periods were considered, the daily rainfall required to initiate landslides first decreased and then leveled at about 50 mm.

One of the landslide zones in Iran is Chaharmahal & Bakhtiari region where the landslides occur during events of prolonged with relatively moderate intensity rainfall; this may be controlled by the antecedent precipitation regime. In recent decades, many landslides occurred and destroyed many roads and buildings. Most of the landslides occurred after rainy periods (Emami, 1998). Although, the relationship between rainfall periods and landslide events in the area is obvious, there is no previous study of rainfall thresholds for landslide initiation. Thus, we tried to determine the empirical antecedent rainfall thresholds for deep-seated landslides.

2 MATERIALS AND METHODOLOGY

2.1 Study area

Chaharmahal & Bakhtiari province with an area of 16,533 km^2 is located in the Central Zagros Mountains, west of Iran. Active tectonic in the Zagros zone has caused the diverse topography and more than 80 percent of the land is mountainous. More than 22 percent of the Zagros geological zone is formed by marl formations and also including clayey-marly deposits (such as western part of the province) and thus, the landslide susceptibility in this area is relatively high.

The kind of precipitation in the province is different from one place to another. For example the rate of snowfall coefficient in the height of Koohrang in different years, has been different from 34 to 59 percents (Chaharmahal Met, 2011). Based on De Martonne (1926) index, the western part of province (landslides area) is classified in humid to very humid type as the mean annual rainfall varies between 600 and more than 1400 mm (Figure 1). The rains are mostly affected by Mediterranean fronts. These fronts come from the west and the southwest and have effect of about 8 months on the region. The

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rainfall begins from October. During 6 months period from November to April the region receives more than 90 percent of its total annual rainfall. Although, the area of Chaharmahal & Bakhtiari province is less than one percent of Iran's total land, this province supplies about 10 percent of water resources in Iran.

In this study, we gathered the exact date for 54 landslides, and these 54 events are the basis for this investigation (Table 1). Figure 2 indicates that the most number of deep-seated landslides (with depth greater than 2 meters) in study region occurred above the 600 mm rainfall line. It could express the effect of hydrologic conditions on the landslide events in the study area.

It is notable that even though the effect of hydrological factors on landslides initiation depends on the other parameters such as topography and geology of the area, but these parameters provide the essential conditions for landslides and thus, the most important triggering factor in the study area is rainfall (Emami, 1998).

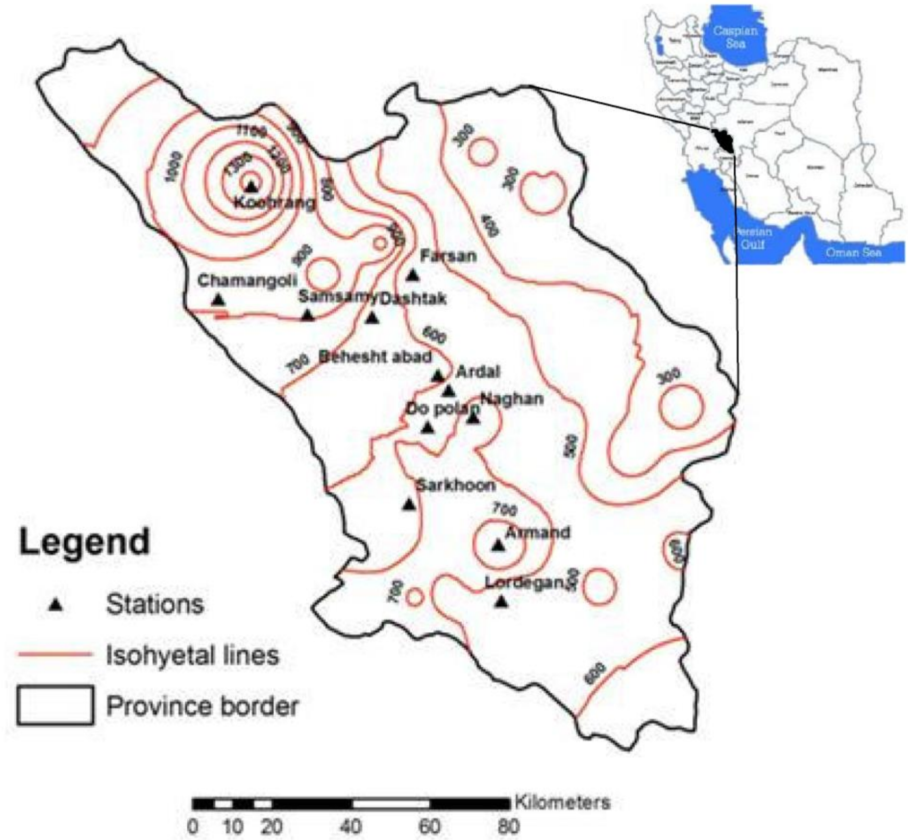

Figure 1 The location of meteorological stations in western part of Chaharmahal & Bakhtiari province and isohyets map of the province.

Table 1 Landslide dates and amounts of rainfall in the days of landslides occurrence (*R*) and cumulative rainfall of the 5-, 10-, 15-, 20-, 25-, 30-day antecedent periods.

No.	Landslide Date	R	A_{5d}	A_{10d}	A_{15d}	A_{20d}	A_{25d}	A_{30d}
1	1991/03/07	9	66	123	170	170	170	184
2	1991/03/26	11.5	107.5	107.5	113.5	156.5	166.5	215
3	1991/03/26	7	107	107	114	189	202	246
4	1992/02/25	37	65	75.5	95	103	114	122.5
5	1992/02/27	12	102	107.5	112.5	132	145	159.5
6	1992/02/28	3.8	209.3	213.2	219.6	257.3	278.9	341.7
7	1992/03/18	16	63	78	78	90	192	197.5
8	1993/02/22	4.5	132	148	151	163.5	181.5	181.5
9	1993/02/23	16	101	104	104	199	250	250
10	1993/03/20	30	70	75	167	172	179	224
11	1993/03/21	15	100	105	172	202	202	254
12	1993/03/21	48.3	204.7	222.9	425.5	500.4	500.4	727.5
13	1993/03/22	8	91	91	114.5	124	124	260.5
14	1993/03/26	2.2	48.7	253.4	271.6	474.2	549.1	549.1
15	1994/03/14	14.4	135.1	138.2	146.7	173.4	182.4	182.4
16	1995/04/24	4.4	72.8	89.4	144.5	160.5	162.3	162.9
17	1996/03/04	4.5	184.3	185.4	253.5	279.3	308.1	352.2
18	1996/03/13	27.9	61.6	158.8	299	300.1	368.2	394
19	1996/03/14	10	48.5	90	181.5	181.5	228.5	241
20	1996/03/26	4.4	144.6	195.9	285.4	334	493.5	523.9
21	1996/03/26	25	81.5	114	172.5	198.5	280.5	305.5
22	1996/04/14	47	76.8	83.8	95.7	143.8	245.9	296.2
23	1996/04/15	2.6	109.9	129.8	141.7	146.3	290.9	342.2
24	1997/03/29	47.9	112.7	177.2	269.6	325.5	365.3	387.7
25	1997/03/30	15	107	141	186	218	240.5	248
26	1997/04/07	15	97	117	156	167	216	248
27	1998/02/12	7.8	107.7	111.9	128.9	131.3	151.3	153.7
28	1998/04/01	1	193.2	235.7	447.1	459.9	478.8	513.2
29	1999/02/21	11	159.7	159.7	196.6	262.7	270.4	326.5
30	1999/03/14	44	61	61	128	154	201	206
31	1999/03/14	29	59	60	130.5	152.5	193	193
32	2002/04/03	23.1	111.6	184.1	242.3	280.7	280.7	280.7
33	2002/04/13	46	32	82.6	96.6	100.9	141.1	149.1
34	2002/04/13	8.5	44.5	65.5	103.5	132.5	171.7	187.2
35	2002/04/14	7	86	88	158	183	225	266

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Table 1 (Continue)

No.	Landslide Date	R	A_{5d}	A_{10d}	A_{15d}	A_{20d}	A_{25d}	A_{30d}
36	2002/04/20	20.2	48.4	113.9	113.9	248.6	321.1	365.1
37	2003/03/26	91.9	52.1	52.1	97.7	184.9	184.9	209.9
38	2003/03/27	14.5	64.5	64.5	72.5	112.5	112.5	116.5
39	2003/03/27	16	78	78	188	227	235	260.7
40	2004/04/05	5.8	176.4	176.4	176.4	176.4	193.9	193.9
41	2005/03/13	20	145	155	155	162	162	162
42	2005/03/14	6.2	238.2	256.2	256.2	283.4	306.4	320.8
43	2005/03/14	4	165	172	172	189	189	193
44	2005/03/14	8	182	190.5	190.5	215.5	215.5	218.5
45	2005/03/14	5.9	295.2	325	325	352.8	373.2	373.2
46	2005/03/14	15.8	402	407.5	407.5	407.5	438.5	438.5
47	2006/02/09	90	57	57	209	242	242	294
48	2006/02/09	110	75	75	248	273	273	346
49	2006/02/09	80	152.8	164.9	387.7	393.4	393.4	393.4
50	2006/02/09	46	113.5	113.5	316.5	348	359.7	416.2
51	2006/02/10	65	89	131	281.5	310	310	377.5
52	2006/04/07	30.1	38.5	130.8	143.8	143.8	143.8	148.8
53	2007/03/28	15.5	125	132	153	153	186	235.3
54	2007/04/15	16	106.5	120.5	156.5	287	300	324.7
37	2003/03/26	91.9	52.1	52.1	97.7	184.9	184.9	209.9
38	2003/03/27	14.5	64.5	64.5	72.5	112.5	112.5	116.5
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40	2004/04/05	5.8	176.4	176.4	176.4	176.4	193.9	193.9
41	2005/03/13	20	145	155	155	162	162	162
42	2005/03/14	6.2	238.2	256.2	256.2	283.4	306.4	320.8
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46	2005/03/14	15.8	402	407.5	407.5	407.5	438.5	438.5
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Table 1 (Continue)

No.	Landslide Date	R	A_{5d}	A_{10d}	A_{15d}	A_{20d}	A_{25d}	A_{30d}
49	2006/02/09	80	152.8	164.9	387.7	393.4	393.4	393.4
50	2006/02/09	46	113.5	113.5	316.5	348	359.7	416.2
51	2006/02/10	65	89	131	281.5	310	310	377.5
52	2006/04/07	30.1	38.5	130.8	143.8	143.8	143.8	148.8
53	2007/03/28	15.5	125	132	153	153	186	235.3
54	2007/04/15	16	106.5	120.5	156.5	287	300	324.7

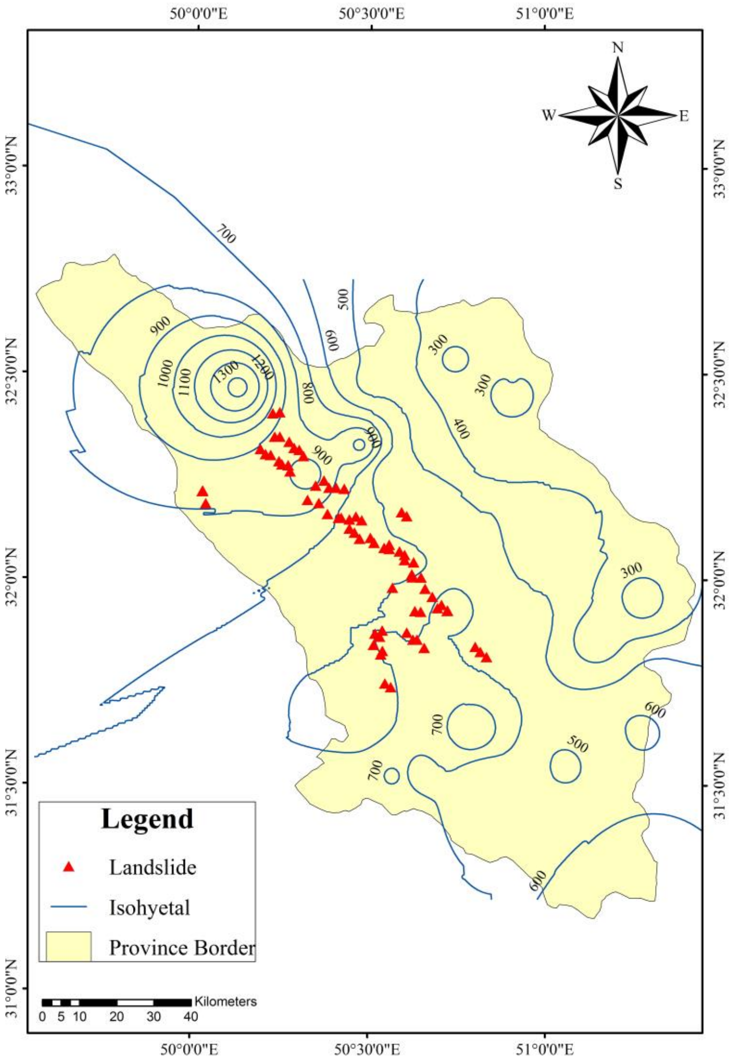

Figure 2 The location of deep-seated landslides (with depth greater than 2 meters) and their relations with isohyets map in the study area.

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2.2 Methodology

The 7 antecedent time periods (5, 10, 15, 20, 25, 28 and 30 days) have been selected for the events examined in this study. First we put the rainfall in the day (24 hr) of landslide event (critical rainfall) on the vertical axis (y) and different cumulative rainfall periods (antecedent rainfall) on the horizontal axis (x), separately. For all of the rainfall periods, correlations between the data were obtained. After plotting data points, the appropriate line (minimum threshold) was drawn based on the lowest points.

Chleborad (2000, 2003) established a rainfall threshold in the Seattle area based on two precipitation measurements: the 3-day antecedent rainfall (*i.e.*, the event rainfall), and the total rainfall for the 15-day period before the 3-day event rainfall (*i.e.*, the antecedent rainfall). In this research, we also used this approach to determine the threshold of antecedent rainfall that triggers landslides.

In some cases there is no meaningful correlation between the rainfall in the day of landslide event and cumulative rainfall in different antecedent periods. In such situations, using the visual criterion is common (Aleotti, 2004). Most commonly, the thresholds are drawn visually, without any rigorous mathematical, statistical, or physical criterion (Guzzetti *et al.*, 2007).

To prevent confusion and to standardize the visual criteria (to determine the type of rainfall threshold), the new definition for the lower threshold is presented. A lower threshold is the line or curve that passes through the most points where all points are located on or above the line. Then, the type of obtained line or curve depends on the number of lowest points (the lowest rainfall amounts that triggered landslides) that the line passes through them.

3 RESULTS AND DISCUSSION

The determination coefficient between the rainfall in the day of landslide event and cumulative rainfall are 0.15, 0.17, 0.2, 0.02, 0.018, 0.015, 0.011 and 0.014 for the 5, 7, 10, 15, 20, 25, 28 and 30-day intervals, respectively. Based on these results, the scattering of the population sample is very high and no significant correlation exists between antecedent and critical rainfall. Aleotti (2004) also concluded that the relevant determination coefficients are 0.17, 0.16 and 0.32 for the 7, 10 and 15 day intervals, respectively. Thus, rainfall in the day of landslide event is not alone criterion for prediction, but it cannot be ignored as the daily rainfall may increase the pore pressure and also weight of soil mass towards critical amounts. In fact, in slopes which are prone to landsliding, a little rainfall also can trigger instability.

Figure 3 shows the mean total rainfall of landslide triggering storms recorded by various rain gauges in the study area versus antecedent time periods (1, 2, 3, 4, 5, 7, 10, 15, 20, 25, 28, 30 days).

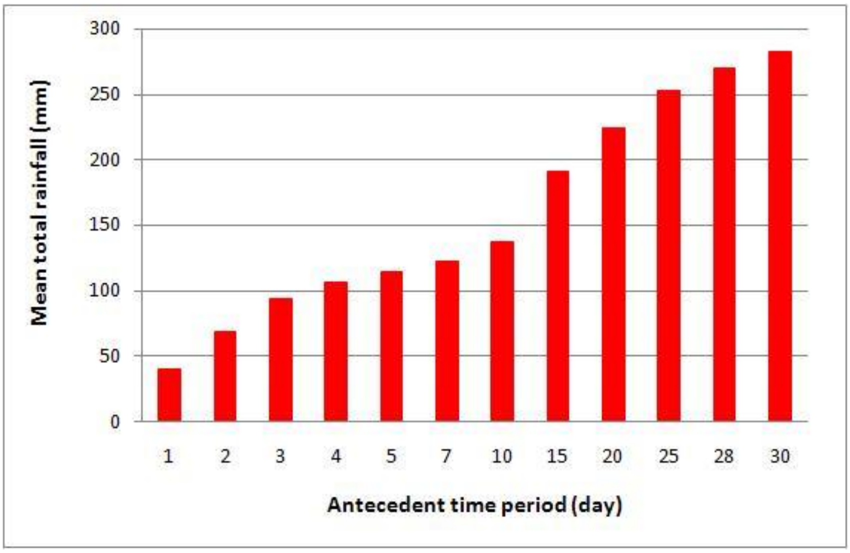

Figure 3 Mean total rainfall of landslide triggering storms recorded at various rain gauges in the study area versus antecedent time periods (1, 2, 3, 4, 5, 7, 10, 15, 20, 25, 28, 30 days).

Based on Figure 3 mean total rainfall of landslide triggering storms for 25 days (antecedent time period) is about 250 mm. According to Corominas and Moya (1999), this amount of rainfall also seems enough for triggering both rotational and translational slides in clayey and silty-clayey formations of Eastern Pyrenees, Spain. It is interesting to note that all of investigated events (critical rainfall) have triggered landslides during the 3-month period of February to April (Table 1). This may imply that the thresholds presented in this research are referring to particular conditions of snowmelt, soil moisture and water tables that usually dominated the study area from February to April.

Figure 4 illustrates the antecedent rainfall threshold for 25, 28 and 30 days in logarithmic scale. The threshold equation of antecedent rainfall (A_d) for the cumulative rain (25, 28 and 30 days) and rainfall in the day of landslide event (R) can be presented as follows:

$$R = 4683 \times A_{25d}^{-1.37} \quad (1)$$
$$R = 4683 \times A_{28d}^{-1.37} \quad (2)$$
$$R = 3157 \times A_{30d}^{-1.29} \quad (3)$$

Rainfall thresholds for the antecedent rainfall of 25 and 28 days (before the landslide event) are the same. This suggests that for antecedent rainfall thresholds, the 28 days time period can be ignored and for the longer antecedent periods than 25 days, the 30 days cumulative rainfall might be considered.

Figure 5 illustrates the antecedent rainfall threshold for the 10, 15 and 20 days in logarithmic scale. Based on the results, the threshold equation of antecedent rainfall (A_d) for the cumulative rain (10, 15 and 20 days) and rainfall of the landslide day (R) can be presented as follows:

$$R = 4223 \times A_{10d}^{-1.52} \quad (4)$$
$$R = 159.9 \times A_{15d}^{-0.83} \quad (5)$$
$$R = 166.4 \times A_{20d}^{-0.83} \quad (6)$$

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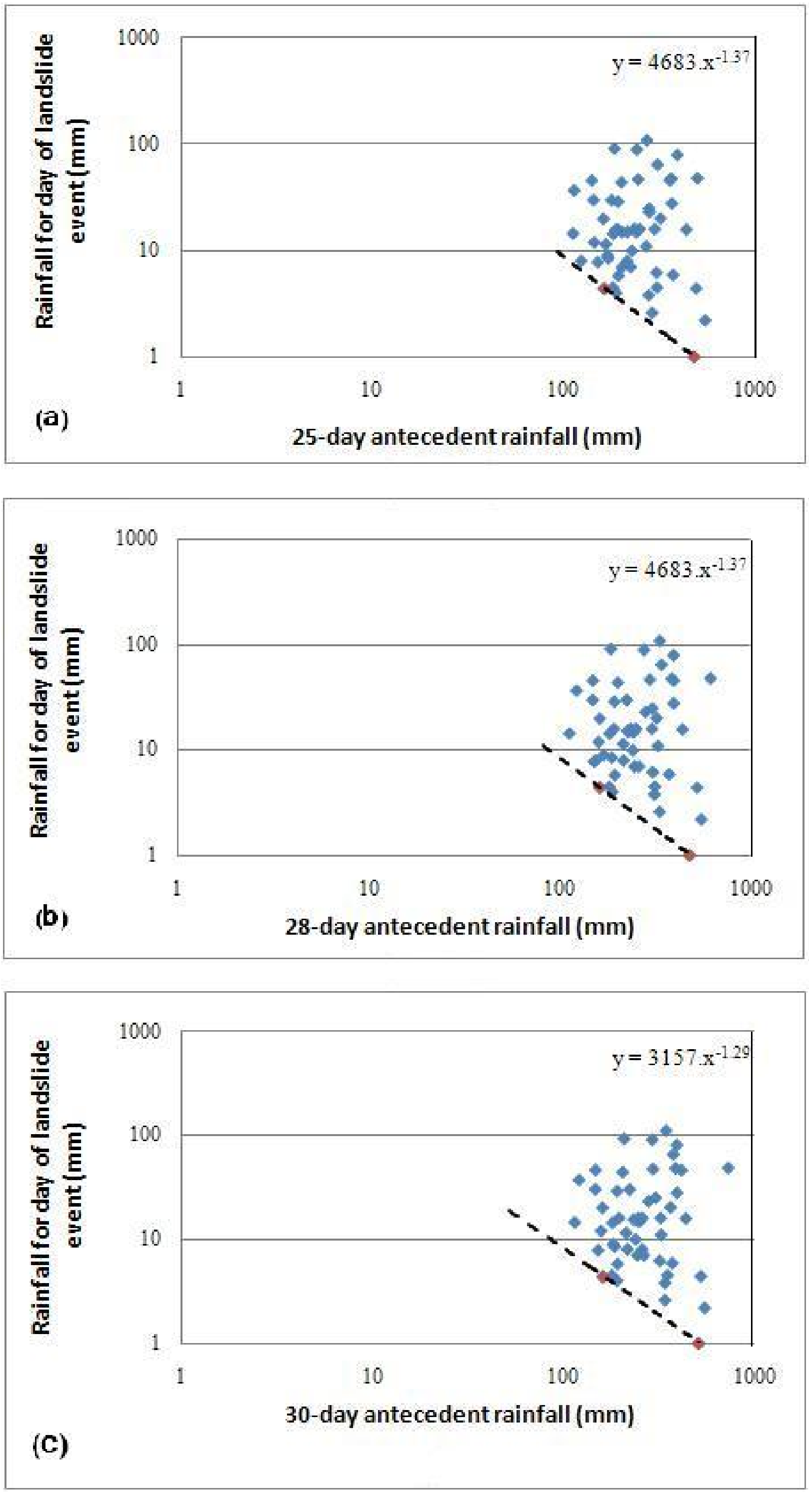

Figure 4 Rainfall for the day of landslide event versus the antecedent 25 (a), 28 (b) and 30 (c) days of rainfall diagram. Red points refer to the lowest amounts of the event and antecedent rainfall that used for drawing the threshold line.

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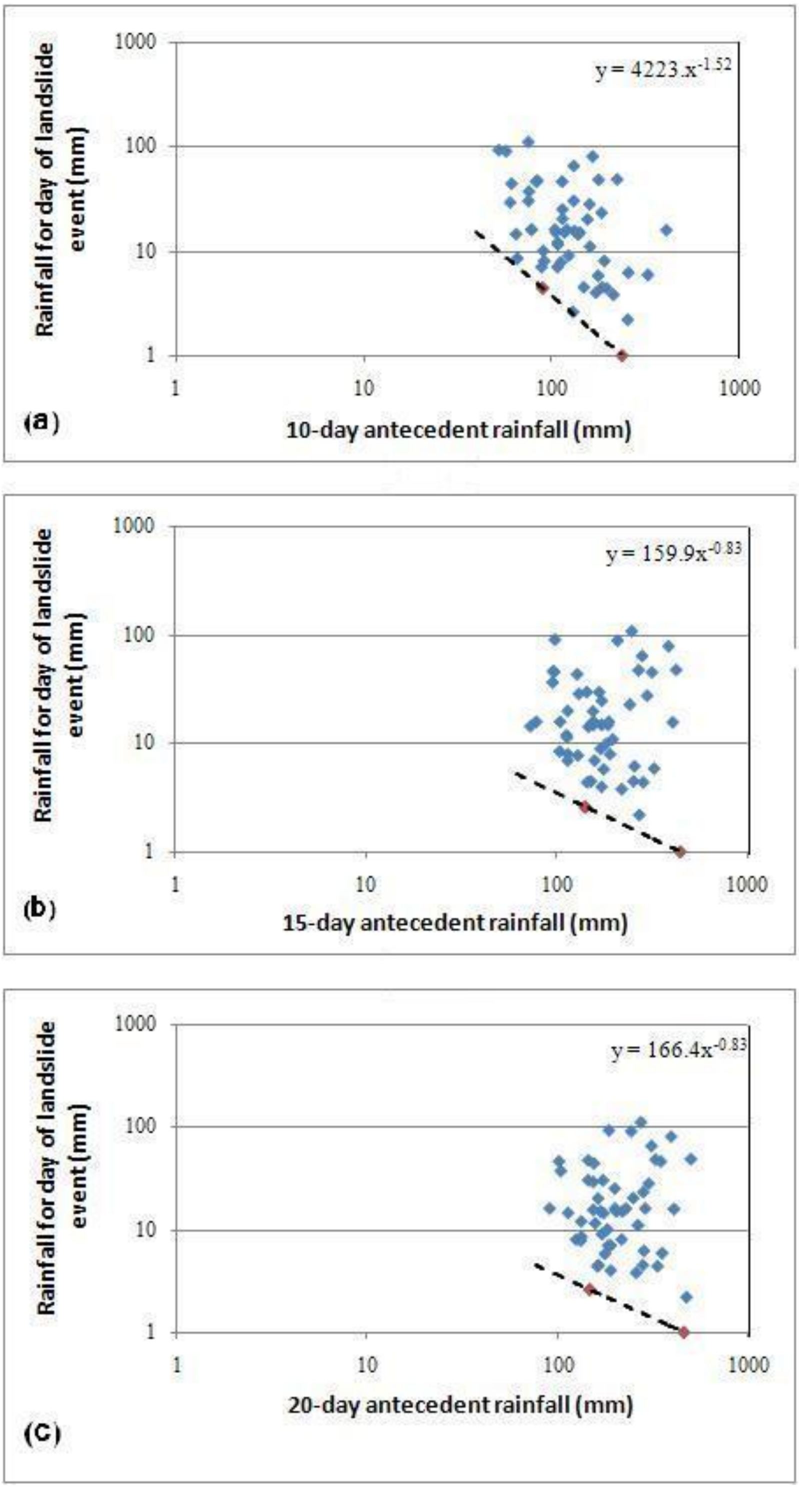

Figure 5 Rainfall for the day of landslide event versus the antecedent 10 (a), 15 (b) and 20 (c) days of rainfall diagram. Red points refer to the lowest amounts of event and antecedent rainfall that used for drawing the threshold line.

By investigating the landslides time of events in our study area, it has been recognized that the equation of threshold curve for 5 days cumulative rainfall can be defined both powered and linearly (Figure 6).

Power and linear equations for the 5 days antecedent rainfall (A_{5d}) and rainfall in the landslide day (R) can be stated as follow:

$$R = -0.008 \times A_{5d} + 2.604 \quad (7)$$

$$R = 20.32 \times A_{5d}^{-0.57} \quad (8)$$

To compare our results with some previous works (*e.g.* Chleborad, 2003), we applied the 3-day rainfall (critical rainfall) and the total rainfall for the 15-day period before the 3-day event rainfall (antecedent rainfall) (Figure 7).

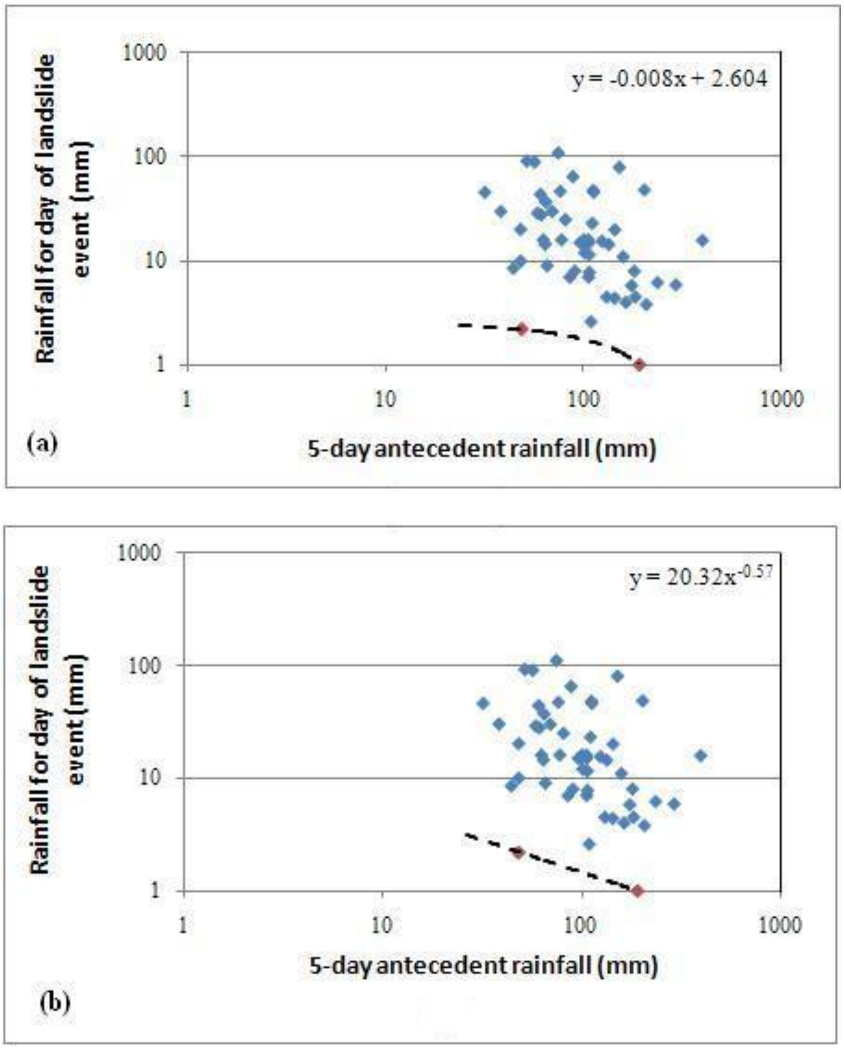

Figure 6 Rainfall for the day of landslide event versus the 5 days antecedent rainfall diagram. Lower threshold curves are recognizable. (a) is the linear regression and (b) is the power regression. Red points refer to the lowest amounts of the event and antecedent rainfall that used for drawing the threshold line.

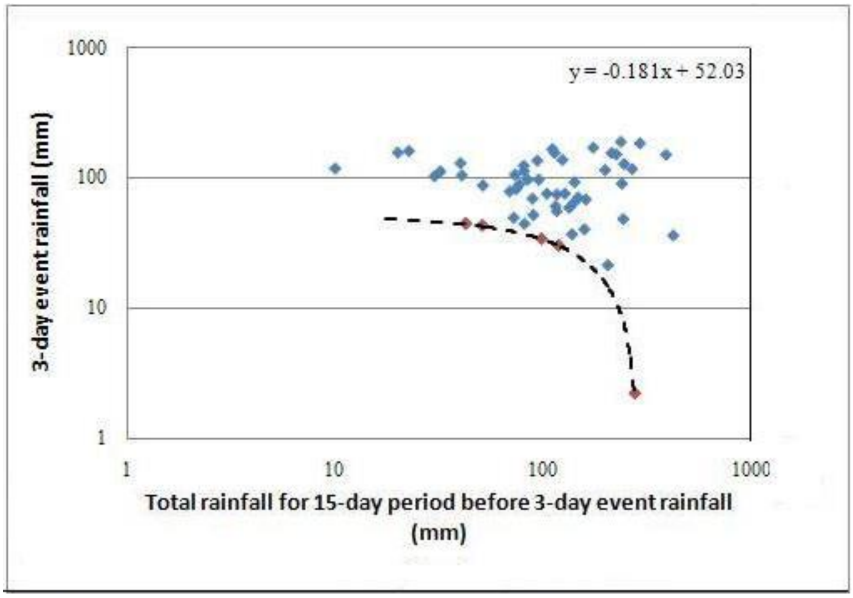

Figure 7 Rainfall for the 3-day event rainfall (critical rainfall) versus the 15-day period before the 3-day event rainfall diagram. Red points refer to the lowest amounts of the event and antecedent rainfall that used for drawing the threshold line.

As can be seen in Figure 7, the equation of antecedent rainfall threshold for the 3-day event rainfall (E_{3d}) and the total rainfall for the 15-day (E_{15d}) period (before the 3-day event rainfall) can be presented as follow:

$$E_{3d} = -\ 0.181 \times E_{15d} + 52.03 \qquad (9)$$

Figure 8 indicated that the deep-seated landslides in the study area have occurred in the wider range amounts of the 3-day event rainfall and the 15-day antecedent period in comparison with Seattle area. Also it can be seen that with decreasing in the amount of 3-day event, required increase in the amount of 15-day event to initiate landslide in study area is dramatically more than Seattle area. These cases could be due to different factors, including: (i) diverse lithological, morphological, vegetation and soil conditions, and (ii) different climatic regimes and meteorological circumstances leading to slope instability. The threshold established by Chleborad (2003) is local but in this study regional thresholds are presented for Chaharmahal & Bakhtiari province; and as expressed by Guzzetti *et al.* (2007) regional thresholds cover wider range of rainfall events.

Based on presented visual standard for drawing thresholds in this study, linear regression was selected for recognition of E_{3d} - E_{15d} threshold. Linear regression passes through more number of the lowest points (4 points) than power regression (2 points).

To investigate the variability of threshold types, in addition to the daily rainfall and the 3 days cumulative rain, the 2- and 5-day rainfall was considered. Figures 9 and 10 showed the 2- and 5-day event threshold for the 15 days antecedent rainfall.

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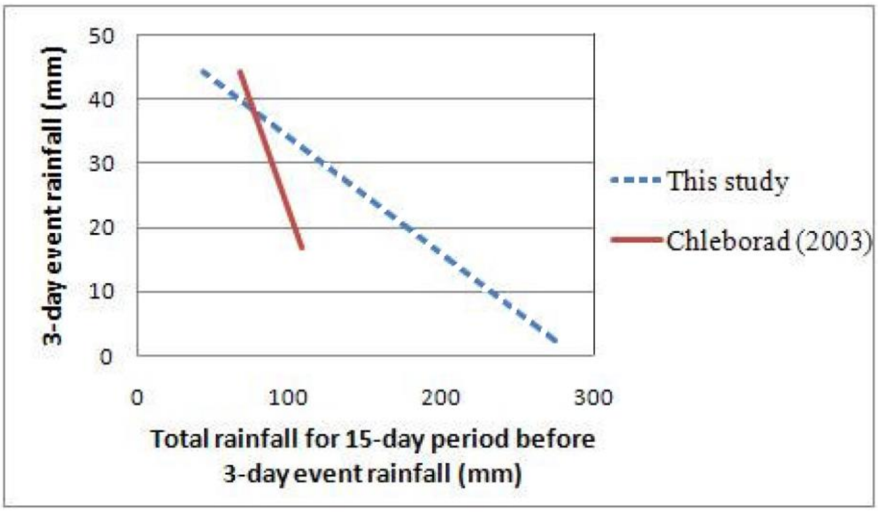

Figure 8 Comparison between suggested lower thresholds for landslides in Chaharmahal & Bakhtiari province and Seattle area (Chleborad, 2003).

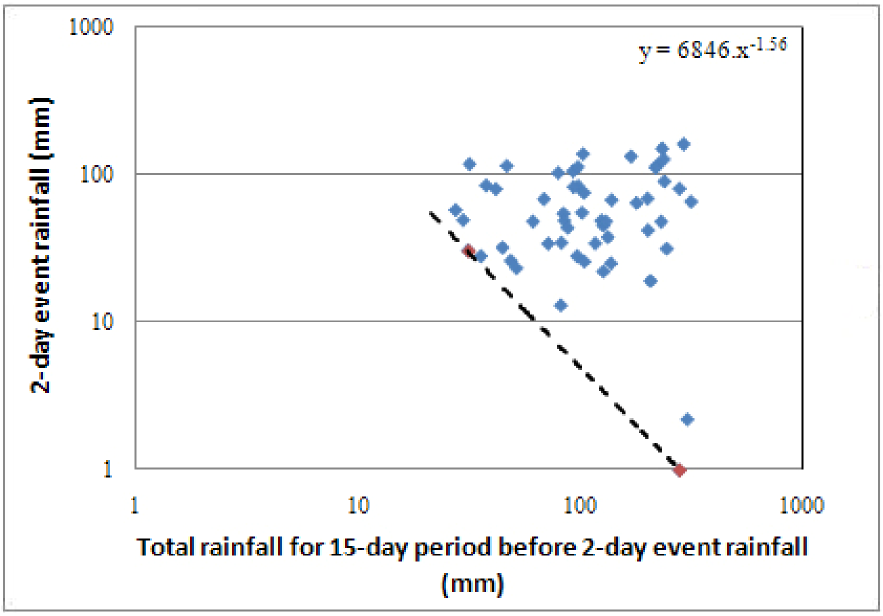

Figure 9 Rainfall for 2-day event (critical rainfall) versus 15-day period before the 2-day event rainfall diagram. Red points refer to the lowest amounts of event and antecedent rainfall that used for drawing the threshold line.

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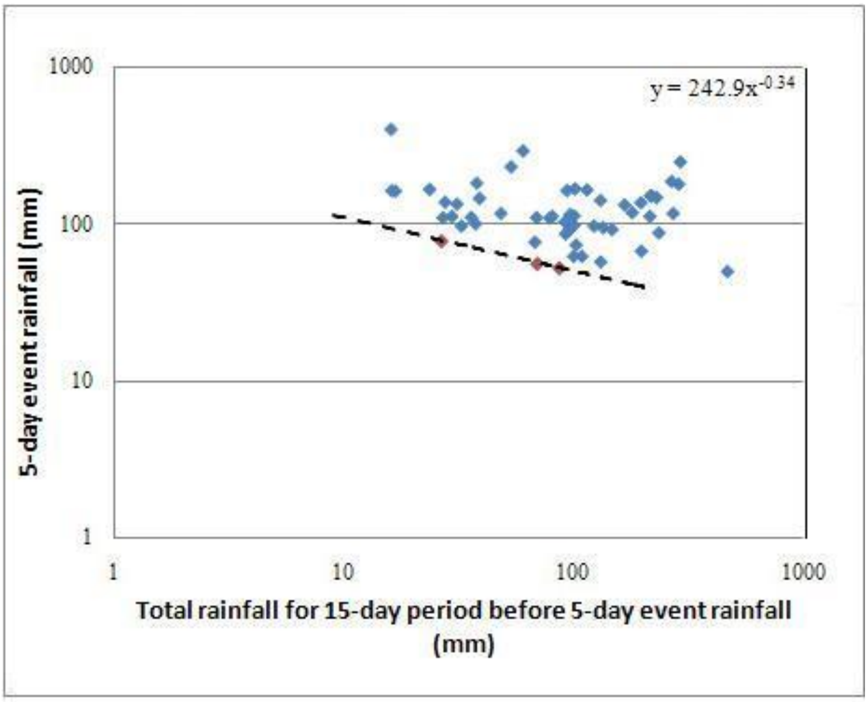

Figure 10 Rainfall for the 5-day event (critical rainfall) versus the 15-day period before the 5-day event rainfall diagram. Red points refer to the lowest amounts of the event and antecedent rainfall that used for drawing the threshold line.

Based on these results (Figsure 9 and 10), the equations of antecedent rainfall threshold for 2-day event (E_{2d}) and the total rainfall for the 15- (E_{15d}) day periods (before the 2-day event) can be formulated as follow:

$$E_{2d} = 6846 \times E_{15d}^{-1.56} \qquad (10)$$

$$E_{5d} = 242.9 \times E_{15d}^{-0.34} \qquad (11)$$

By considering the 2 and 5 days event instead of the daily rainfall, no changing in the type of the threshold equations (power regression) was happened.

4 CONCLUSION

Since most of the landslides in the study area have occurred after a rainy period, this study was carried out to investigate relationship between landslides time of occurrence and antecedent rainfall characteristics. It means that the lower thresholds for landslide initiation in the study area can be established theoretically. To determine the more effective antecedent rainfall threshold, among the time periods 5, 10, 15, 20, 25, 28 and 30 days, the results of 5 days and shorter time periods appear not logically connected. Although, these rainfalls might increase the pore pressure and weight of soil mass towards the critical amounts and thus may play a key role in hillslopes destabilization. However, it seems the crucial soil moisture to trigger a landslide is related to more than 10 days antecedent rainfall. Most of landslides occurred by cumulative rainfall for more than 10 days. Thus, the antecedent time periods for the events examined in this area were 10, 15, 20, 25, 28 and 30 days. We have also established the antecedent rainfall thresholds according to 15-day antecedent period for 2, 3 and 5 days rainfall events. Overall, by investigating the rainfall for the days around the occurrence time of soil failures and different time periods of cumulative rainfalls before landslides, a statistical model can be presented for each hydroclimatic region as a tentative landslide warning system. As the hydrological and mechanical behavior of different soils in the study area are completely different, more research is needed to investigate the relation between instability and rainfall characteristics in homogenous soil classes, separately (especially in clayey-marly deposits of Zagros zone).

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آستانه‌های بارندگی پیشین برای وقوع زمین‌لغزش‌های عمیق در استان چهارمحال و بختیاری

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چکیده بارندگی به عنوان یکی از مهمترین عوامل ماشه‌ای زمین لغزش‌ها شناخته شده است. پژوهشگران همواره تلاش کرده‌اند تا میزان بارندگی مورد نیاز برای وقوع زمین‌لغزش در مناطق مختلف جهان را تعیین کنند. یکی از مناطق لغزش‌خیز کشور که هرساله خسارات زیادی را متحمل می‌شود، استان چهارمحال و بختیاری (به ویژه غرب آن) می‌باشد. از آنجایی که ارتباط معنادار بین بازه‌های زمانی بارانی و وقوع زمین لغزش‌ها در استان چهارمحال و بختیاری به اثبات رسیده است، در این مطالعه تلاش شده تا آستانه‌هایی براساس بارندگی پیشین برای زمین‌لغزش‌های عمیق ارائه شود. بدین منظور و با توجه به بررسی منابع، بازه‌های زمانی ۵، ۱۰، ۱۵، ۲۰، ۲۵، ۲۸ و ۳۰ روزه‌ی قبل از گسیختگی‌ها در نظر گرفته شدند، همچنین با استفاده از رویکرد تجربی دیگری تلاش شد آستانه‌هایی نیز برای بارندگی پیشین ۱۵ روزه براساس بارش‌های تجمعی ۲، ۳ و ۵ روزه پیشنهاد گردد. نتایج نشان داد که مگر در شرایط استثنایی، تنها با مطالعه بارش‌های پیشین در بازه زمانی کمتر از ۱۰ روز نمی‌توان به نتایج منطقی دست یافت؛ و همچنین میانگین مقدار بارندگی مورد نیاز برای وقوع گسیختگی در بازه‌های زمانی ۱۰ و ۳۰ روزه به ترتیب ۱۴۰ و ۲۸۰ میلی‌متر خواهد بود. در نهایت پیشنهاد می‌شود مطالعات بیشتری در زمینه ارتباط بین مشخصات بارندگی و ناپایدار شدن دامنه‌ها به ویژه بر روی پهنه‌های (نهشته‌های) رسی- مارنی غرب استان صورت بگیرد.

کلمات کلیدی: استان چهار محال و بختیاری، بارندگی پیشین، حد آستانه، زمین لغزش

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