Dryland Soil Research, Vol. 1, No. 1, pp. 11-22, Summer 2024.
Type of article: Case study, Available online at www.dlsr.iut.ac.ir.

Republished from:
https://doi.org/10.47176/jsssi.01.01.1009

The relationship between channel width changes with confinement index and flood power of an extreme flood (Case study: Ilam Dam)

Zahra Khanbabaei[1†], Ghobad Rostamizad[2], Ebrahim Moghimi[3] and Mehran Maghsoudi[4]

[1] PhD Student, [3] Professor and [4] Associate Professor, Faculty of Geography, University of Tehran, Iran
[2] Assistant Professor, Agricultural and Natural Resources Research Center, AREEO, Zanjan, Iran

†Corresponding Author Email: khanbabaei@ut.ac.ir

(Received 2022/02/02, Accepted 2022/20/09)

Abstract

Extreme floods are able to execute river geomorphological variations with a wide and substantial geological changes. Former studies of extreme floods have reported a reach of geomorphic replies from negligible change to catastrophic channel change. This article provides an evaluation of the geomorphic effects of a scarce, great value event that occurred in the Ilam Dam upstearim, on 29 October 2015. Variations in geomorphic replies among reaches are examined in the context of changes in flood power, channel competence and lateral confinement index by the use of field survey and Satellite Images (IRS). In this research which is focused on the plan of spatial units, channel width variations and calculation of peak discharges were used to estimate cross-sectional stream power and unit stream power. The analysis was performed for the widening (width ratio) at reach scale. The total data set includes 38 reaches. Because of the 2015 flood, the largest value of widening was 29 m (Reach 13) and it demonstrated a 100% change in the channel width. Flood power peak was calculated 10631 W m^{-2} along the rather confined reaches (Reach 31) and was much lower along the unconfined reaches. The tendency of high stream power values, and resultant high erosion rates, within the confined and partly confined reaches is a subordinate of the higher energy slope of the steeper.

Keywords: Ilam Dam, extreme flood, lateral confinement index, Reach, stream power.

1. Introduction

Extreme floods execute substantial river geomorphological variations and these changes can have a wide and pervasive geological legacy (Alho et al., 2005; Baynes et al., 2015; Carling, 2013; Carrivick et al., 2010; Guan et al., 2015). Whereas extreme floods are, by description, rare and occur during a very short period of time, field evidence has shown that hydro-geomorphic responses to floods may affect flood hazard and risk because of changes in channel morphology and to subsequent river hydraulics (Borga et al., 2014; Fewtrell et al., 2011; Lane et al., 2007; Marchi et al., 2009). It is commonly accepted that variations in discharge, sediment value, and bar can lead to changes in channel capacity, planform, and planimetric configuration (Williams and Wolman, 1984). According to the fact that geomorphic position provides a framework for aquatic and coastal ecosystems, these changes can lead to variations in the combination, density, and successional patterns of biological communities (Gregory et al., 1991; Kondolf and Micheli, 1995). Therefore, it has been identified that a determination of the flows that control the specifications and dimensions of a channel known as the prevailing discharge is necessary to minimize or avoid the impacts of the arrangement of a flow (Andrews and Nankervis, 1995). Recent studies have also reported on the value and geomorphic variation resulting from scarce floods that qualify changes to channel geomorphology ranging from lowly to baleful (Costa and O'Connor, 1995; Kale and Hire, 2004; Magilligan et al., 2015; Magilligan, 1992; Phillips, 2002; Thompson & Croke, 2013; Wolman and Miller, 1960). Many studies have explained the concept of peak discharge, which was proposed by Wollman and Miller (1960), noting that instead of an individual discharge, it is more appropriate to consider a range of discharges (Surian et al., 2009). Geomorphological effects of floods are interpreted based on observations of the processes in the Polish Carpathians and their foreland as well as in the Darjeeling Himalayas and their foreland. In the Carpathians, the author examined the effects of extreme rainfalls and floods, paying attention to their frequency at different time intervals and different sizes of the catchments. In the area of tectonic subsidence at the foreland of the Sikkim-Bhutanese Himalayas, the aggradation may enter upstream into the mountain interior (Barrocu & Eslamian, 2022). Ongoing research is in progress to investigate the role of key drivers of geomorphic change such as flood power (Kale, 2008), sequencing of flood events (Magilligan et al., 1998), and spatial variations in valley floor form (Cheetham et al., 2010; Fuller, 2008). The increasing access and use of high-resolution topographic data has opened up the possibility of more fast and spatially vast evaluations of flood-related geomorphic change.

In November 2015, following intense and sudden rains, a large flood occurred in Ilam province with a maximum momentary discharge recorded at about 230 m^3 s^{-1}. According to the evidence, this flood has been unprecedented in the last few decades. This flood caused severe loss of life and financial and also caused major changes in the river bed and was associated with a significant Transverse expansion. Since the hydro-geomorphological causes of the occurrence of such an event with a long return period are not known, for a real understanding of the relationship between the flood and the morphology of the system, it is necessary to have a detailed analysis of the geomorphological situation of the events that are able to transport the bed and flood materials. On the other hand, because the expansion rate of the channel was variable in different sections of the studied river, it was possible to investigate the influencing and controlling factors that caused the variation in the behavior of the river. Since fewer studies have been conducted in this field, an integrated and interconnected method can be the key to a proper understanding of these events and their morphological response. The presence of important agricultural facilities and urban infrastructures upstream of the Ilam Dam, damages caused by geomorphological changes along the river with their role in natural, economic and social changes were the reasons behind investigating this river. This article presents an evaluation of the geomorphic effects of a rare high value event by the use of field survey and Satellite Images. This study experiments the hypothesis that differences in geomorphic reply between the selected partly confined and unconfined reaches can be explained in terms of relative differences in flood power and degrees of valley confinement.

2. Materials and Methods

2.1. The study area

The research study is located in the Ilam Dam basin in the north-east of Ilam city, West of Iran (33°38′ 15″ N, 46° 25′ 22″ E), with an area of 475 km^2. This catchment area is located between Ilam basin, Shirvan Chardavol, Darrehshahr and Changuleh. The lowest elevation in the basin is 935 m and the highest elevation on the north of the basin is 2615 m above sea level (Fig. 1). Three major rivers in this basin, Golgol, Chaviz and Ama located on the upper reaches of the Ilam Dam. The climate of the region is semi-humid (De Martonne classification), the average rainfall is 557 mm and the average daily potential evapotranspiration is 5 mm. The studied basin is located on the northwestern part of the Zagros folded belt. Generally, there are two types of rocks, including limestone and marl, on the surface of the basin. Marl stones located at the basin surface are very weak in relation to erosion factors and annual significant volumes of sediments due to erosion of these stones and floods from the basin are released.

In this study focused on delineation of spatial units, a channel width variations and calculation of peak discharges used to calculate cross-sectional stream power and unit stream power.

2.2. Delineation of spatial units and morphological characteristics

The first step of this research involved (i) analysis of morphological properties and (ii) plan of spatial units. The data used in this step were collected from Satellite Images, Digital Elevation Model (DEM) with a spatial resolution of 10 m, and topographic maps with 1:25000 scale.

The analysis was performed by geographic information system (GIS) software. The analyzed morphological properties were alluvial plain areas, lateral confinement pre-flood channel areas and channel slope. Definition of the alluvial plain contained low terraces and present floodplain (i.e., surfaces that can be some meters higher than the floodplain) (Surian et al., 2016). The alluvial plain was mainly identified using the DEM and topographic maps. As for lateral confinement, three valley settings were differentiated (Brierly and Fryirs, 2005): laterally unconfined, confined, and partly confined reaches.

Lateral confinement was defined by combining two aspects: the confinement index (Ci) which is defined by the ratio between the alluvial plain width (Wpl) and the channel width measured before flood (Rinaldi et al., 2013), and the degree of confinement, which is the percentage of channel banks directly in contact with hill slopes or ancient terraces (Brierly and Fryirs, 2005). The DEM was used to calculate channel slope, as the difference in elevation was divided by the planimetric distance relative to each reach. Delineation of spatial units was carried out according to the approach proposed by Rinaldi et al (2013), which is a modification of the approach by Brierley and Fryirs (2005). According to that approach, stream sectors were defined as macro reaches having similar characteristics in terms of lateral confinement, while reaches are homogeneous in terms of channel morphology (channel pattern, width, and slope) and hydrology. Then, the reach scale (reach length was commonly from 200 to 620 m) was used for an overall assessment of the magnitude of channel changes and also for a preliminary investigation. The studied reaches are the basis of the research for studying the river geomorphic variations in response to an extreme flood. 38 reaches were selected in the whole basin from which the first 20 ones belonged to the Golgol, the 13

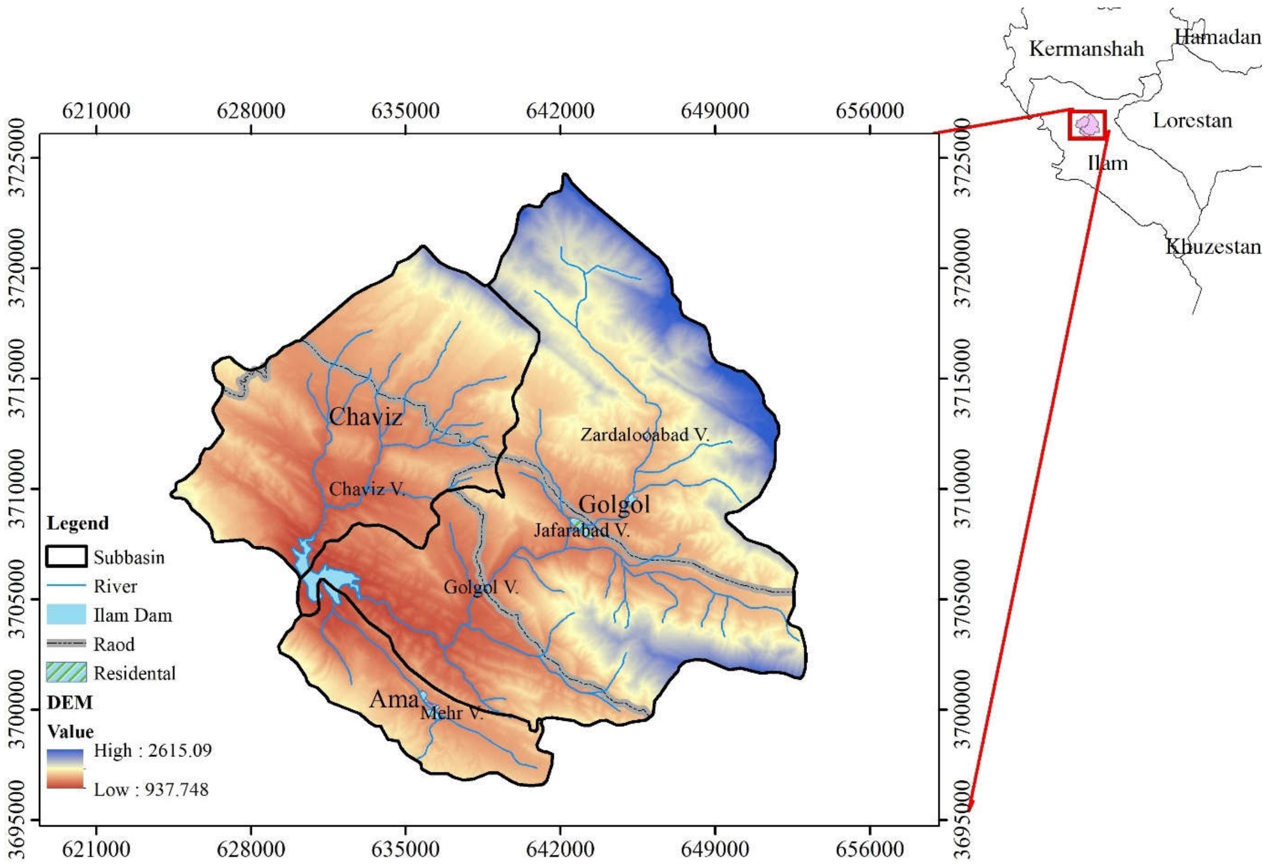

Fig. 1. Location of the study area

subsequent reaches were related to the Ama, and the 5 last reaches of the Chaviz basin were selected and studied.

2.3. Morphological changes: Analysis of the channel widening

Morphological changes induced by the 2015 flood were assessed by field surveys and interpreted through high-resolution images (2.5 m) taken by the IRS satellite. The dominant process observed in the study reaches was the channel widening, which was analyzed in details by comparing Satellite Images taken one year before (2014) and one year after the flood (2016).

To assess changes in the channel width, channel banks and islands were digitized on pre- and post-flood images. The Channel width was calculated after dividing the channel area by the length of the reach, and changes in the channel width were expressed as a width ratio (channel width after/channel width before the flood) (Krapesch et al., 2011). Measurement of the width before and after the flood in each of the reaches was done in AutoCAD software environment (Fig. 2).

2.4. Hydraulic analysis

In this study, to estimate hydraulic indices there was a need to a peak discharge in each reach, that should be used in an appropriate method for its estimation. In this study, the curve number method was used to estimate the runoff height. For this purpose, using Arc Hydro software, each basin was subdivided into smaller sub-basins which are enclosed to each reach. Then, the number of curves was determined in each of the sub-basins and finally, using the SCS method, determination of runoff and peak discharge in each of the reaches were performed (for example, in the reach of number 36, parameters such as S, CN, Q, Tp, and Tc were calculated as 88.69, 74.12, 29.35 mm, 2.01 hours and 1.39 hours, respectively). The hydrological groups of soil in the studied basin included A, B, C and D. Because of its simplicity, the SCS method has become very popular among engineers and experts as one of the most commonly used methods, mainly for small urban and agricultural basins, moderate natural basins, and for basins where there are no runoff measurement data (Mishra et al., 2006). In addition, it is a predictive model that records environmental inputs and is a well-documented method widely accepted in the United States and other countries (Kumar et al., 2010).

By estimating the peak discharge, three hydraulic variables were calculated based on the reach scale.

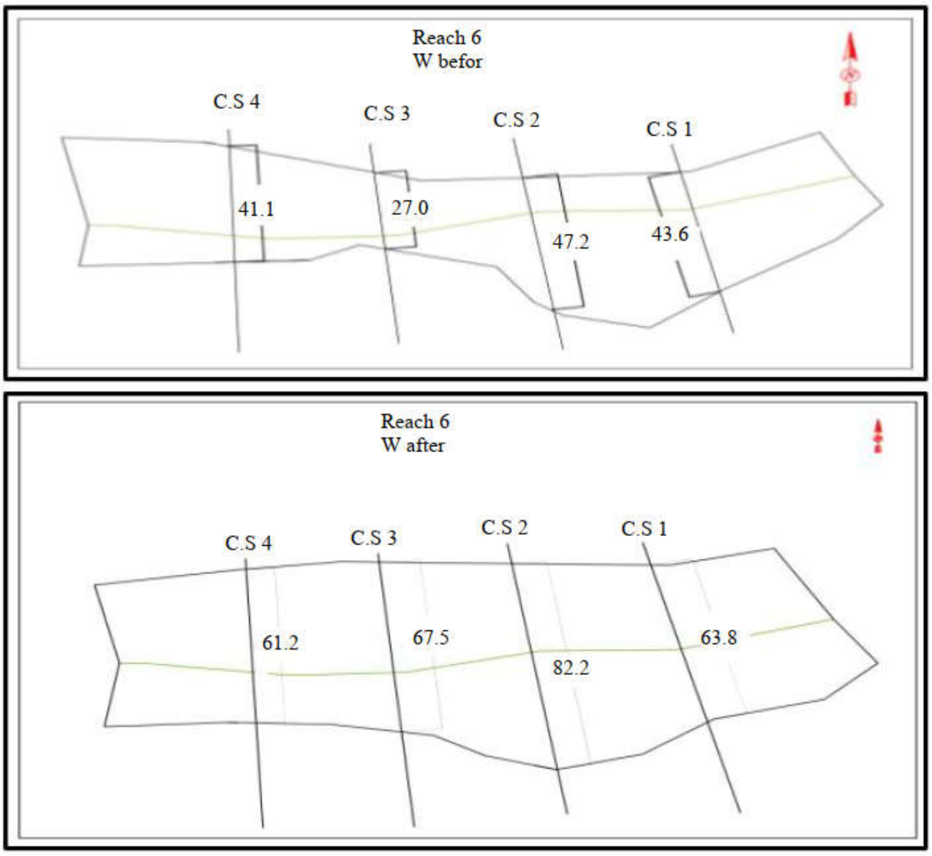

Fig. 2. Measuring the variations in the width of the reach 6 before and after the flood in different cross sections (CS)

Stream energy was analyzed taking into account three hydraulic variables closely related to the flood power: the cross-sectional stream power (W m^{-1}) was defined as

$$\Omega = \gamma QS \qquad [1]$$

Where γ is the specific weight of water (N m^{-3}), Q is the discharge (m^3 s^{-1}), and S is the channel slope.

Unit stream power (W m^{-2}) obtained by dividing the channel width measured before and after the flood. (Surian et al., 2016).

$$\omega_{\text{before}} = \Omega / \omega_{\text{before}} \qquad [2]$$

Where Ω is the cross-sectional stream power (Nm^{-3}) and ω_{before} is the channel width measured before the flood (m).

$$\omega_{\text{after}} = \Omega / \omega_{\text{after}} \qquad [3]$$

Where Ω is the cross-sectional stream power (Nm^{-3}) and ω_{after} is the channel width measured before the flood (m). The flowchart of the research process is shown in Fig. 3.

3. Results and Discussion

3.1. Investigation of the hydrological characteristics of the flood event

In order to achieve the research objectives and to determine the geomorphic response of the Mountain Rivers upstream of the Ilam Dam to extreme floods, Hydrograph charts were drawn up and analyzed. At the Golgol meteorological station, three rainfall events occurred on 28, 29, and 30th October, amounting to 51, 105, and 91 mm respectively (Fig. 4).

The flood started at 9am on the 28th of October in 2015 and continued until 9am on the 30th of October. During this flood, there were three maximum instantaneous discharges (98, 230 and 134 m3/s) in the sub-basin of Golgol (Fig. 4) but in the sub-basins of Chaviz and Ama only one maximum instantaneous discharge (140 and 58 m^3/s respectively) was recorded. The reason for this, according to experts from Ilam Regional Water Company, is the destruction of the hydrometric station in these rivers due to the extreme flood on the 29th of October. In Fig. 5, the position of the rain gauge stations used for their data is shown in relation to the desired reaches.

3.2. Reaches situation in terms of lateral confinement

As shown in Fig. 6, the reaches are distinguished by the type of lateral confinement. This situation includes confined (c), partly confined (pc), and laterally unconfined reaches (uc). The degree of confinement is

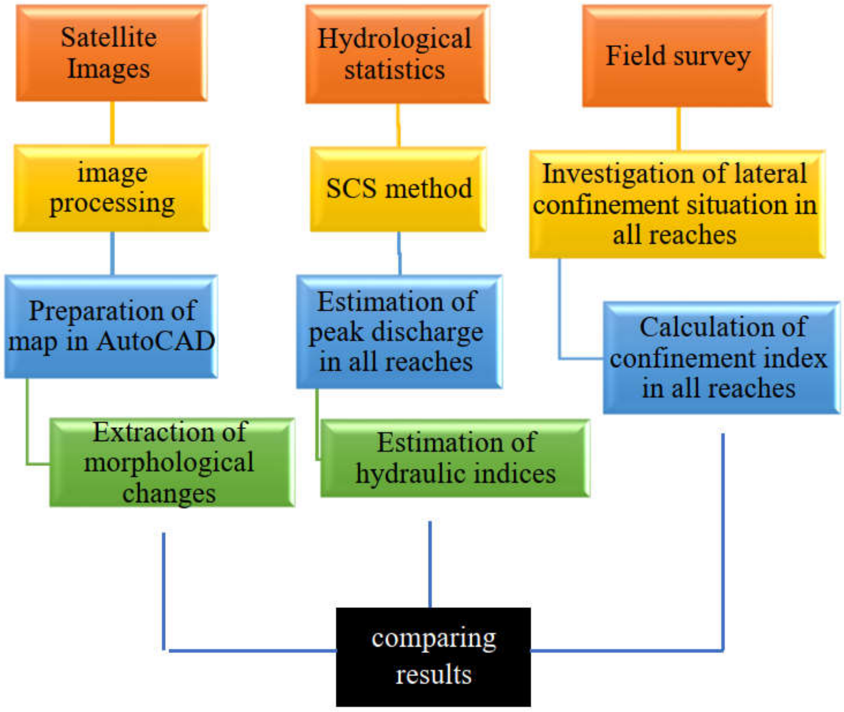

Fig. 3. The flowchart of the research process

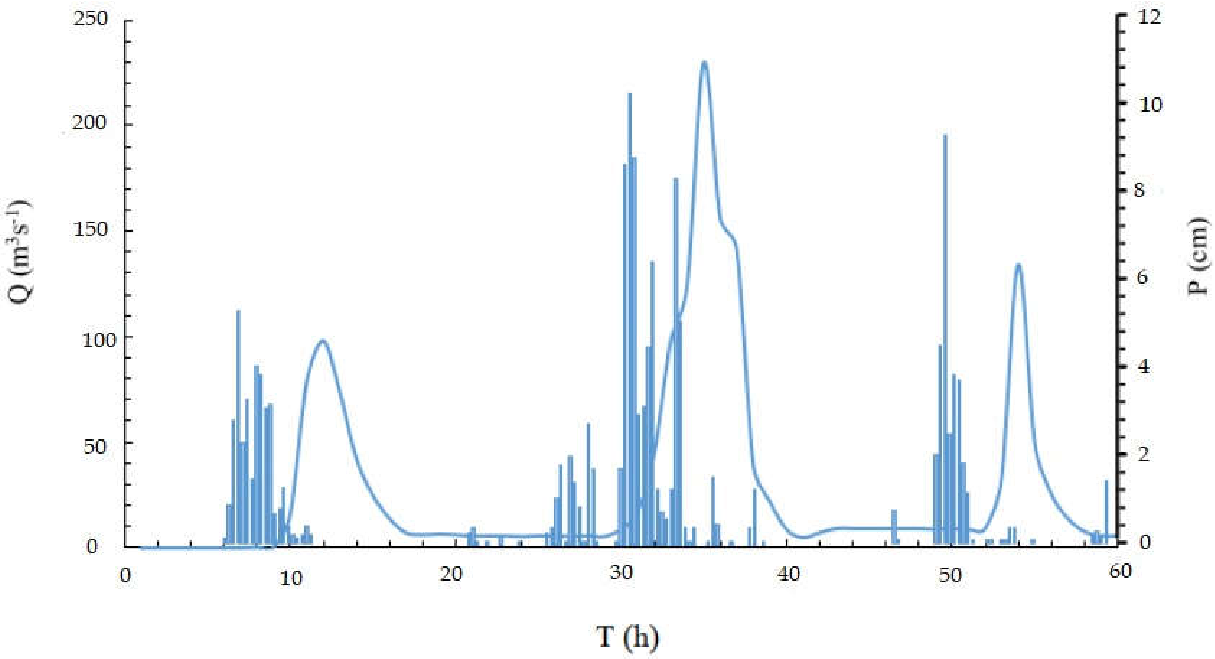

Fig. 4. Flood hydrograph chart on the 28th, 29th and 30th of October in the sub-basin of Golgol

the percentage of channel banks directly in contact with hill slopes or ancient terraces and the confinement index is defined by the ratio between the alluvial plain width and the channel width. Table 1 shows width of the alluvial plain (W_{pl}) and confinement index (C_i) in all reaches. Figure 6 shows examples of lateral confinement situation in the studied basin.

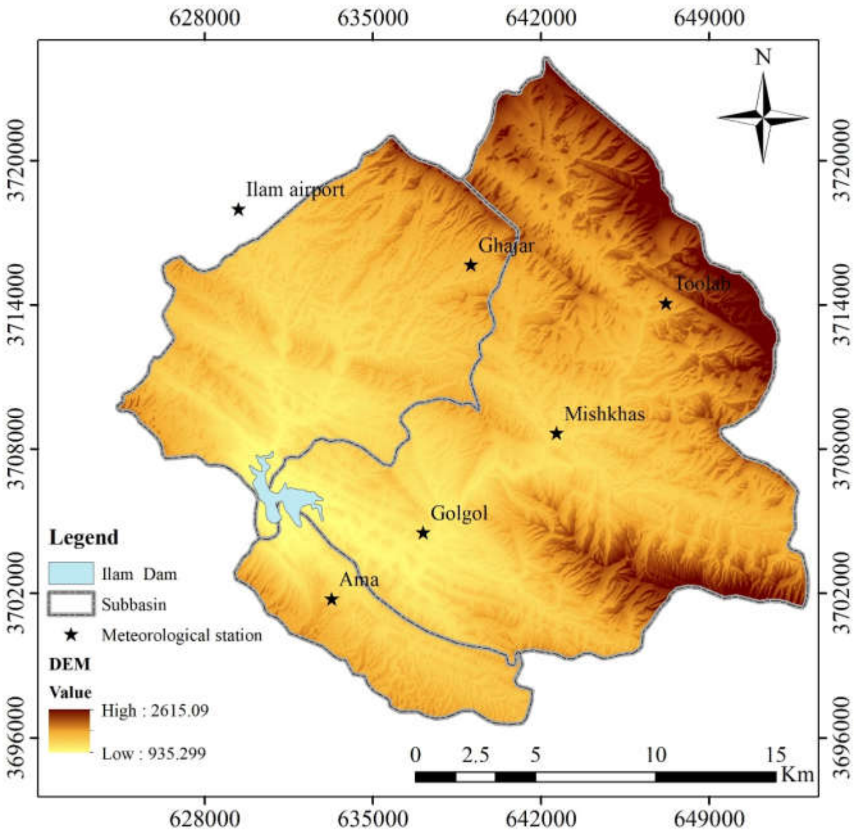

Fig. 5. Position of rain gauge stations in the studied basin.

3.3. Morphological changes at the reach scale

In this section, the morphological characteristics of the studied streams and channel changes that took place during the 29 October 2015 flood are illustrated at the reach scale. A summary of the results of changes in channel width for the main partly confined and unconfined reaches within the 38 reaches is illustrated in Table 1 and Fig. 7. The minimum, average, and maximum length of the 38 study reaches is 197, 404, and 620 m, respectively. All these reaches display typical characteristics of mountain streams and cover relatively wide ranges in terms of channel slope, channel width, and lateral confinement. Channel slope varies between 0.97% and 17.05%, with 5.2% being the average for the 38 reaches; channel width ranges from 2 to 29 m, being 12.5 m on average; confinement index ranges from 1 to 5.03 (Table 1). The expansion of the channel occurred at 37 reaches, while the channel changes in reach 27 was not detected. The most intense changes occurred along the Golgol river (reaches 12 to 14), in which the channel's width increased by more than 20 meters.

3.4. Estimate of peak discharge

Estimates of the peak discharge, cross-sectional stream power, and unit stream power at the reach scale are reported in Table 2. The peak discharge ranged from 20 m^3s^{-1} (reach 37, a small tributary of Chaviz River) to 364 m^3s^{-1} (reach 20 of Golgol River). Cross-sectional stream power varied between 24,941 and 159,120 W m^{-1} in the reaches 24 and 18 respectively. The unit stream power was calculated between 778 and 10,631 W m−2 by using the channel width before the flood, while it was calculated between 489 and 5639 W m−2 using post-flood channel width using post-flood channel width ranged between 489 and 5639 W m^{-2}.

4. Conclusion

This study presented an assessment of the channel changes and flood power of the October 2015 flood in the upper reaches of the Ilam Dam, Iran. The results indicate that the expansion process is principally controlled by two factors: stream power and lateral-confinement, which both are effective according to the conditions of the study area, but other factors should also be investigated (Khanbabaee et al., 2019). The expansion of the channel occurred at 37 reaches, while the channel changes in reach 27 was not detected because of lateral confinement on both sides. The most intense changes occurred along the Golgol river (reaches 12 to 14), in

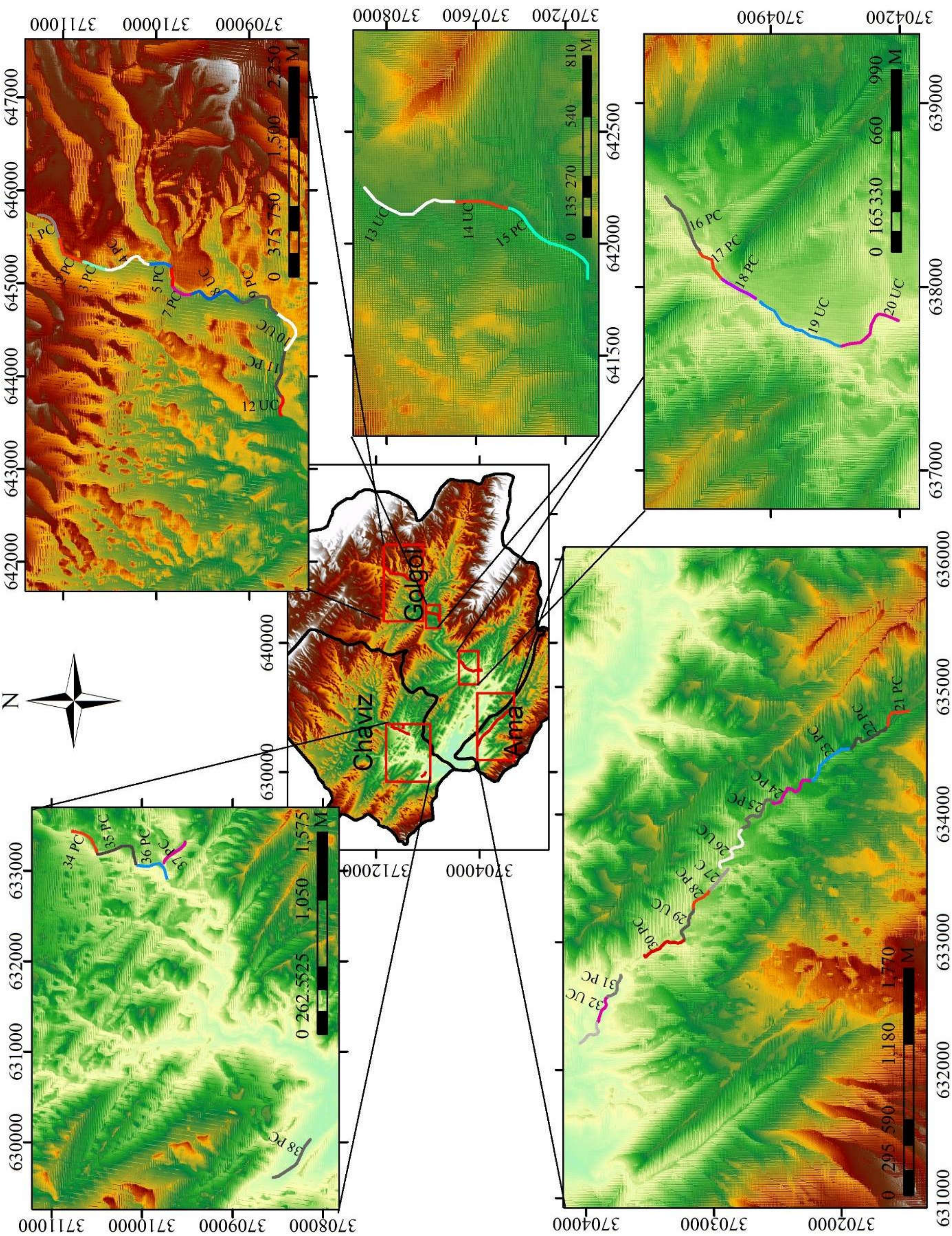

Fig. 6. Reaches situation in terms of lateral confinement (c: confined, pc: partly confined and uc: unconfined reaches)

Table 1. Morphological characteristics and channel width changes at reach scale.

reach	L (m)	S (mm^{-1})	Type of reach	W_{pl} (m)	C_i	W_{before} (m)	W_{after} (m)	W_{ratio}
1	392	0.022	Pc	61.22	2.75	22.24	37.31	1.68
2	413	0.036	Pc	36.98	2.69	13.76	22.03	1.60
3	241	0.063	Pc	29.99	1.86	16.12	28.30	1.76
4	553	0.055	Pc	39.91	2.36	16.88	20.99	1.24
5	247	0.042	Pc	52.62	3.16	16.67	28.54	1.71
6	197.3	0.029	Uc	88.99	2.21	40.25	67.16	1.67
7	241	0.033	Pc	73.36	1.76	41.61	51.64	1.24
8	607	0.029	Uc	77.61	2.59	30.00	52.16	1.74
9	547	0.054	Pc	53.38	2.01	26.50	37.51	1.42
10	526	0.056	Uc	68.22	2.95	23.10	38.13	1.65
11	508	0.033	Pc	85.42	2.16	39.47	58.84	1.49
12	242	0.045	Uc	99.40	5.03	19.78	48.51	2.45
13	463	0.043	Uc	86.36	3.03	28.47	57.68	2.03
14	243	0.013	Uc	84.83	4.43	19.14	39.35	2.06
15	518	0.063	Pc	50.58	2.35	21.52	33.05	1.54
16	364	0.028	Pc	117.15	2.76	42.49	56.84	1.34
17	207	0.029	Pc	66.47	2.23	29.84	42.40	1.42
18	213	0.047	Pc	37.29	1.14	32.66	34.86	1.07
19	540	0.011	Uc	93.19	2.25	41.36	67.80	1.64
20	420	0.010	Uc	79.51	2.01	39.52	59.50	1.51
21	279	0.096	Pc	58.71	1.83	32.06	41.26	1.29
22	385.5	0.082	Pc	28.42	1.58	17.96	26.46	1.47
23	422.1	0.070	Pc	67.15	2.30	29.26	44.97	1.54
24	437	0.034	Pc	74.61	2.33	32.03	43.58	1.36
25	433.3	0.052	Pc	67.40	2.63	25.58	39.22	1.53
26	426.9	0.033	Uc	101.84	3.53	28.88	51.49	1.78
27	222.1	0.036	C	-	-	11.42	11.42	1.00
28	212.1	0.042	Pc	53.85	4.06	13.25	22.01	1.66
29	287.5	0.075	Uc	41.59	2.84	14.64	27.44	1.87
30	368.9	0.032	Pc	32.91	1.92	17.15	20.46	1.19
31	227.5	0.162	Pc	25.80	2.12	12.19	22.97	1.89
32	229	0.052	Uc	45.30	2.09	21.71	36.02	1.66
33	235.7	0.034	Pc	49.95	1.45	34.37	43.78	1.27
34	410.1	0.089	Pc	83.29	1.59	52.45	60.69	1.16
35	593.5	0.055	Pc	53.84	1.95	27.62	35.16	1.27
36	479.3	0.041	Pc	49.79	2.00	24.85	33.12	1.33
37	351.8	0.170	Pc	41.68	1.98	21.10	29.37	1.39
38	620.4	0.076	Pc	41.04	1.68	24.46	33.79	1.38

L - Reach length; S - channel slope; Wpl - width of the alluvial plain; Ci - confinement index (Wpl/Wbefore); Wbefore - channel width before the flood; Wafter - channel width after the flood; Wratio - channel width after the flood/ channel width before the flood. **Note**. C: confined; P.c: partly confined; U.c.: unconfined.

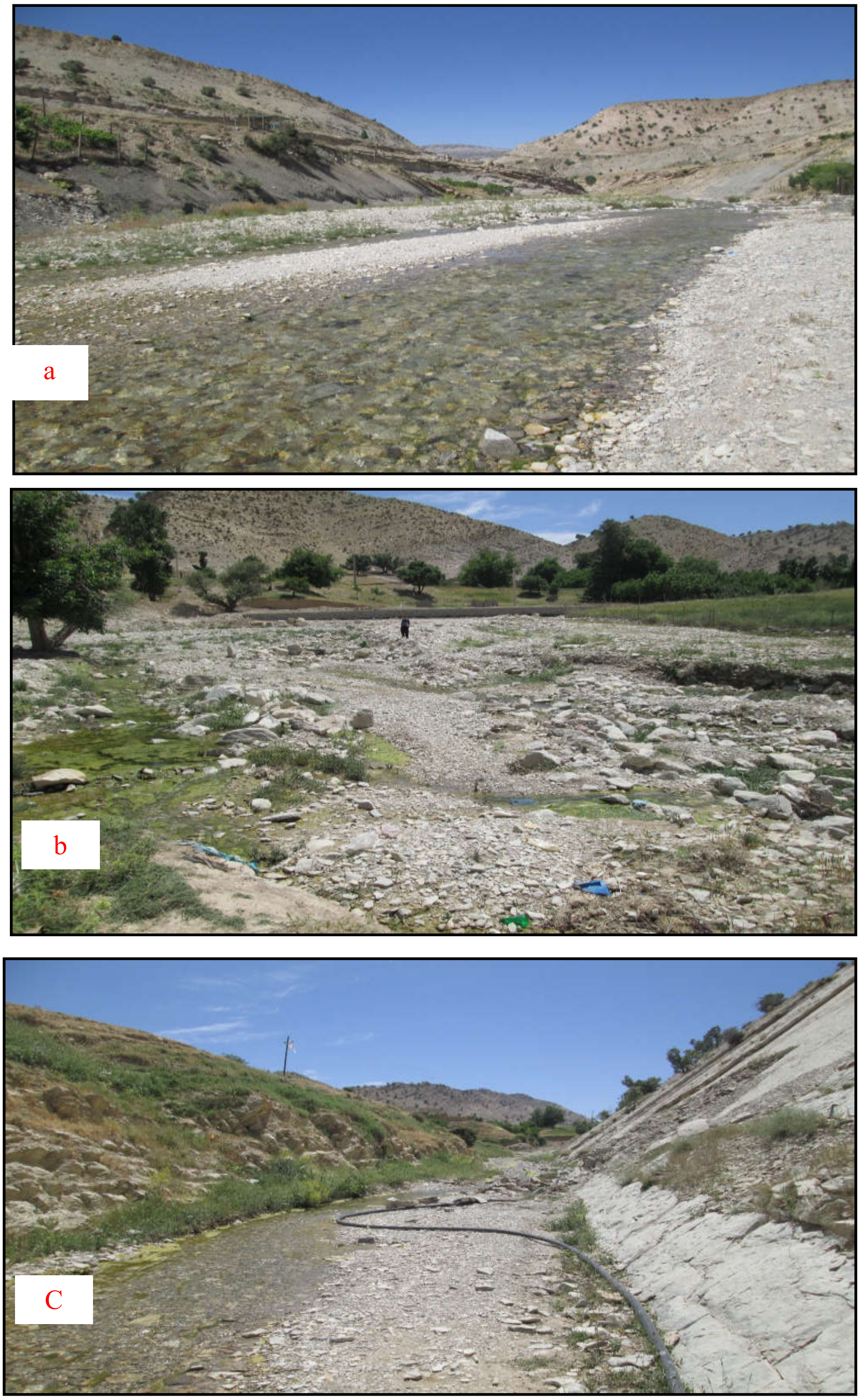

Fig. 7. Examples of lateral confinement situation in the studied basin (a: reach 15 of the Golgol river is partly-confined, b: reach 26 of the Ama river is unconfined and c: reach 27 of the Ama river is confined.

Table 2. Hydraulic characteristics of the studied reaches

reach	Q_{pk} (m^3s^{-1})	Ω(wm^{-1})	ω_{before} (wm^{-2})	ω_{after} (wm^{-2})
1	173.7	38151.4	1715.8	1022.5
2	189.0	66150.6	4807.3	3002.2
3	189.5	117889.9	7315.2	4165.3
4	191.3	103984.7	6158.8	4954.6
5	192.3	79873.2	4791.3	2798.4
6	204.1	58831.0	1461.6	876.0
7	204.6	66377.3	1595.4	1285.3
8	205.1	58450.7	1948.3	1120.6
9	206.3	110066.2	4152.8	2934.6
10	206.9	112876.7	4886.4	2959.9
11	208.1	66296.7	1679.7	1126.7
12	209.1	92020.5	4653.0	1896.8
13	209.5	87742.9	3081.7	1521.3
14	252.4	31043.1	1621.5	789.0
15	257.4	157627.3	7324.4	4769.9
16	335.7	92165.8	2168.9	1621.6
17	340.5	95331.9	3194.7	2248.6
18	347.5	159120.2	4872.4	4564.7
19	352.3	39454.6	953.9	581.9
20	364.3	34745.6	879.2	584.0
21	62.6	58944.0	1838.6	1428.7
22	72.3	57992.6	3228.8	2191.8
23	74.8	50972.5	1742.3	1133.4
24	75.2	24941.2	778.6	572.4
25	76.2	39049.0	1526.3	995.6
26	77.6	25176.8	871.8	489.0
27	79.3	27862.7	2439.2	2438.8
28	79.6	32483.4	2451.9	1878.7
29	80.0	58696.3	4008.5	2138.7
30	80.9	25584.6	1491.6	1250.3
31	81.4	129553.9	10631.4	5639.1
32	81.8	41656.4	1918.6	1156.6
33	82.0	27694.7	805.8	632.5
34	175.1	152984.7	2917.0	2520.8
35	176.5	95114.1	3443.2	2705.4
36	187.9	75552.3	3039.8	2281.2
37	20.8	34669.4	1642.8	1180.4
38	67.8	50557.7	2066.7	1496.1

Qpk - peak discharge; Ω - cross-sectional stream power at the peak discharge; ω_{before} - unit stream power calculated based on the channel width before the flood (Ω/Wbefore); ω_{after} - unit stream power calculated based on the channel width after the flood (Ω/Wafter).

which the channel's width increased by more than 20 meters. Referring to Fig. 2 and Table 1, and observing the type of reaches, it is seen that these were unconfined reaches and did not have a limitation to expand the channel. In general, it can be said that unconfined reaches have endured more width extension than the confined and the partly unconfined reaches. It was also observed that the unconfined reaches have high width ratio rates. Therefore, it can be concluded that index confinement is directly proportional to the expansion of the channel width. The findings of this study confirm the results of Saurian et al. (2016) and Rinaldi et al. (2013). Also, the presence of high stream power values within the confined reach is a function of the higher energy gradient of the steeper slopes. The results showed that the stream power was higher in the steep slopes and the slope reduction was effective in reducing the stream power. Therefore, the partly unconfined reaches with higher slope had a large amount of unit stream power (ex: reaches 3,4,15, 31) while in the unconfined reaches, the unit stream power significantly reduced (ex: 19, 20, 26, 33). The results of Thomson and Crook are also in the same direction. It should be noted that in this research, two power units are used. The unit stream power was calculated based on the channel width before the flood, and the unit stream power was calculated based on the channel width after the flood. Because peak discharge was used for stream power calculation to be aware that neither pre-flood nor post-flood channel width is actually appropriate for the estimation of the unit stream power, the most appropriate would be the width at the flood-peak time. The fact that using the pre-flood width gives better relations with the degree of channel widening (i.e., width ratio) could suggest that most width changes occurred after the flood peak. This result also confirms the results of (Moraru, 2017; Righini et al., 2017; Surian et al., 2016).

Acknowledgments

This study is extracted from a doctoral thesis and the authors are grateful to the Supervisor and Advisor as well as the regional water company of Ilam province for their sincere cooperation with us in providing the data.

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