

Driving factors of short-term channel changes in a semi-arid area (Sahand Mountain, northwestern Iran)

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Abstract Rivers change through time in response to upstream and downstream controls and may change over very short time periods (i.e., few years), in particular when human impact affects fluvial systems. In the Lighvan River catchment, a semi-arid mountainous area in northwestern Iran, remarkable changes in the fluvial environment and channel morphology have taken place over the last few years. The aim of this paper is to explain driving factors of channel changes along the Lighvan River, in a 16-km-long reach, over the period 2000–2012. Data and methods used include maps and field survey to quantify channel changes; analysis of hydrological data (precipitation and discharges); Landsat images for land-use classification and then evaluation of possible changes in flood peak discharge by SCS method; and calculation of unit stream power changes. In general, the channel underwent incision (up to 1 m) and narrowing (up to 18 m), although aggradation occurred in few cross sections in the upstream part of the study reach and widening in few cross sections in the downstream part. Investigation of causes of these changes showed that magnitude of annual peak discharges increased over the period 1991–2012, and it can be suggested that such increase is related to natural causes (i.e., increase of precipitation) and human impact so that both human and natural factors had a role in the recent evolution of the Lighvan River. Channelization and increase of peak

discharges (due to an increase of precipitation and land-use changes) have been the main drivers of channel evolution.

Keywords Channel morphology · Incision · Narrowing · Human impact · Lighvan River

Introduction

Channel changes are driven by natural processes and human interventions. Topographic conditions, hydrological data, and climatic factors can lead to an increase or decrease in water flow and sediment fluxes and thus changes in channel morphology. In the meantime, human role, in terms of direct or indirect interventions, can be crucial for channel adjustments. Evidence of channel changes can be detected by direct observations, historical records, sedimentary evidence, dating techniques, and inferential reasoning (Brierley and Fryirs 2005). Interpretation of channel changes requires quantitative analysis of channel morphology and controlling factors and identification of links between channel changes and controlling factors (Ziliani and Surian 2012). This implies that such interpretation is always affected by a certain degree of uncertainty that may be reduced when the number of controlling factors is relatively small or when data set is very robust. Nevertheless, analysis and interpretation of channel changes are crucial issues for effective river management.

Several studies have analyzed the role of human impact in changing channel dynamics and morphology (e.g., Goude 1993; Surian 1999; Vanacker et al. 2005; Gregory 2006). Human impact includes interventions at reach such as channelization (e.g., Surian and Rinaldi 2003; Chin 2006), dams (e.g., Gordon and Meentemeyer 2006), and

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sediment mining and at catchment scale such as land-use changes (e.g., Booth 1990, 2001; Graf 1975, 2000; Clark and Wilcock 2000; Paul and Meyer 2001; Karwan et al. 2001; Baillie and Davis 2002; Nelson and Booth 2002; Boyle 2004; Liebault et al. 2002; Kesstra et al. 2005; Grable and Harden 2006; Kang 2007; Ward 2007; Galster 2008; Kang et al. 2010). Land-use changes have a twofold impact in fluvial systems for example decreasing or increasing water and sediment discharge. This may lead to a different channel response and metamorphosis. Deforestation and associated phenomena as overgrazing and increasing agricultural pressure cause commonly an increase of sediment supply which leads to aggradation and channel widening. When natural reforestation occurs or planned afforestation is carried out, there is a decrease of sediment supply and channel narrowing (e.g., Liébault and Piégay 2002), armouring development, bed incision, and change in channel pattern (e.g., from braiding to meandering) (e.g., Boix-Fayos et al. 2007).

Semi-arid regions are the most sensitive to changes in driving factors such as natural (e.g., Sreedevi et al. 2013) and human (e.g., Mallick et al. 2014) factors, and channel response is particularly noticeable in upland areas, where sensitivity to change is enhanced by strong coupling between river channels and hillslopes. Intensification of human activities in these areas has changed regime and altered the morphology of the valleys, increasing probability of large floods (Bayati Khatibi 2006). In the study area, a semi-arid mountain catchment in northwestern Iran, human interventions (e.g., channelization, bank protection, sediment mining) without taken into account natural forms and processes have caused alteration of the fluvial environment and changes in river morphology. According to the Regional Water Authority of East Azarbaijan, flood damages have increased in the Lighvan River catchment during the last 10 years. The aim of this work is to explain the channel changes that took place in the period 2000–2012 and, more specifically, to investigate the role of human factors versus that of natural processes (e.g., natural changes in flow regime). A better understanding of driving factors of short-term evolution of the Lighvan River is crucial for an effective management and to prevent adverse effects of channel changes (e.g., damage to structures, increase of flood risk). This study was carried out in the Lighvan River for several reasons. First, there is a good availability of data (e.g., topographic surveys and hydrological data) and studies in comparison to other Iranian rivers. Second, few studies have analyzed channel changes in semi-arid environment. Last, but not least, river management, specifically in relation to flood risk, is and will be a key issue in this mountain area.

Study area

General setting

The Lighvan catchment is located in the northern slope of Sahand Mountain (northwestern Iran) and it has an area of 142 km² (Fig. 1). Main physiographic characteristics of the catchment are reported in Table 1. According to topographical characteristics the study area can be divided into two units: high mountain and high plateau. Igneous rocks, Quaternary in age, and alluvium tuff with the relatively large thickness outcrop in the catchment. Soils are young and relatively undeveloped and consist of two categories, entisol and inceptisol.

There are two hydrological stations within the catchment. The Lighvan station is located in the upper part, while the Hervi station at the outlet of the catchment (Fig. 1). The average annual precipitation in the period 1991–2012 was 333 mm and 250 mm, respectively, at Lighvan and Hervi station. Average annual temperature of the Lighvan basin is 6.4 °C, and average temperatures in August (the warmest month) and February (the coldest month) are 18.2 °C and –5.1 °C, respectively. The climate, according to classification categories of Ball (1991) and available statistical data, is cold semi-arid, shifting to cold semi-humid in the highest portions of the catchment (Karami and Khatibi 2005).

The length of the Lighvan River is 28.5 km. Lighvan Chai river flow is perennial because the regime of the river is snowy and the catchment has the permanent snow cover in different altitudes so that snowmelt is effective and remarkable in the river perennial flow and therefore its drainage basin density is low.

The average annual discharge is 6.6 m³/s at the outlet of the catchment (Hervi station). Lighvan valley has U-form in the upper part of the catchment where the river is mainly confined. Gradually, the valley bottom becomes wider, and the Lighvan River flows in semi-confined and unconfined conditions (Bayati Khatibi 2004). The length of study reach is 15.8 km, from Lighvan village to Hervi village. The channel is composed of cobbles and gravels, and has mainly plane-bed morphology, according to Montgomery and Buffington (1997) classification (Fig. 2). Minimum, maximum, and average channel widths are 4.4, 17.6, and 10.4 m, respectively (Table 2).

Human impact

The study area is not densely populated but there are four villages, Sefidehkan, Lighvan, Beiragh, and Hervi, and urbanization is growing due to tourism. Suitable areas (i.e., flat areas) for cultivation and urbanization are

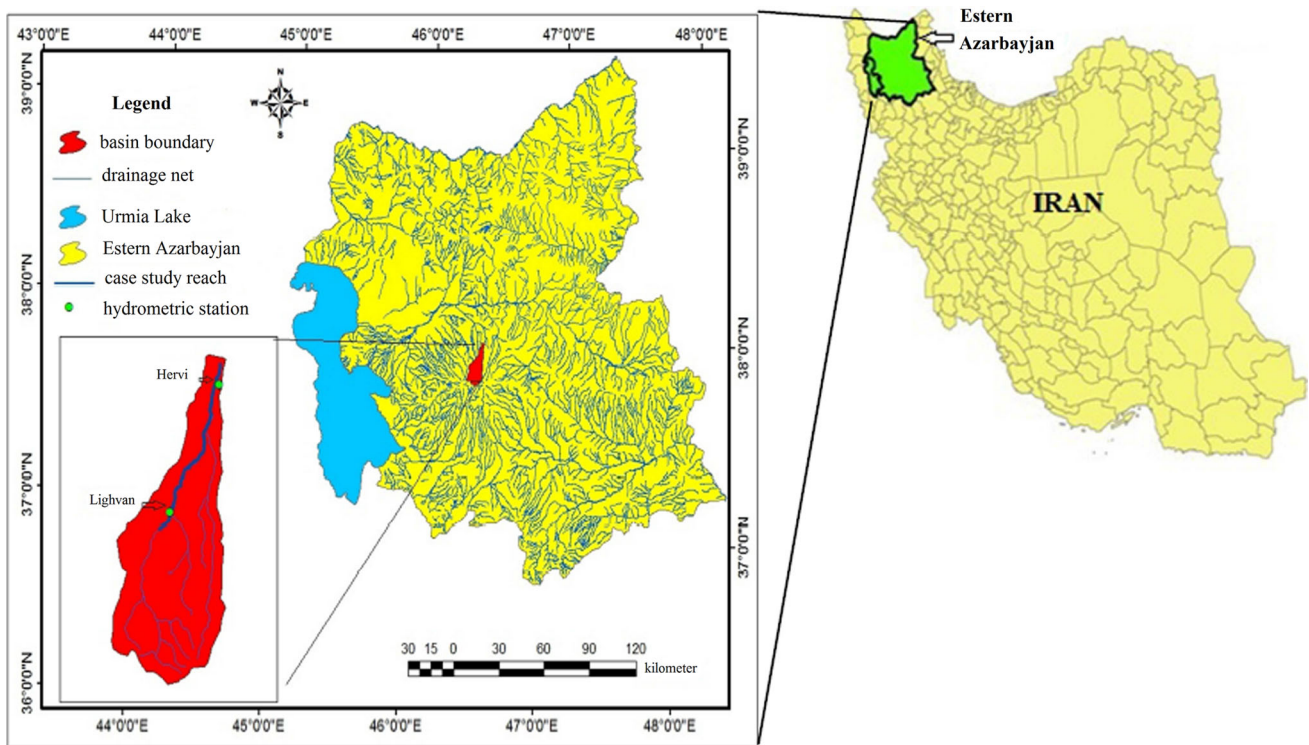


Fig. 1 Location of the study area

Table 1 Physiographic characteristics of the Lighvan River

Elevation in the catchment (masl)			Drainage basin density (km/km ²)	Catch.area (km ²)	Catch. perimeter (km)	Mean slope of catchment (%)	Mean slope of main river (%)	Length of main river (km)
max	average	min						
3570	2851	1880	2.898	142	60.9	14.2	4.6	28

limited, and therefore an increasing use of floodplains, and of less steeper slopes, has taken place over the last few years. According to the Ministry of Agriculture of East Azarbaijan Province (2010), there have been many changes in pasture land, rained and irrigated agriculture, and orchard areas in recent decades which are related to population changes, type of management, and the rural residents knowledge. It should be noted that the construction of villas and residential areas has grown dramatically along the Lighvan River and within the catchment area in the recent years. Besides, construction of new roads on steep slopes has been a remarkable change in this area. In terms of river management, several channelization works (i.e., walls, bank protection structures) have been carried out over the last few years (Fig. 3). Finally, according to the reports of the National Geosciences Database of Iran (2010), mineral extraction for construction has largely increased at the beginning of the century.

Methods

Channel change analysis

In order to analyze short-term changes of the Lighvan channel morphology, two sets of cross sections were compared. The first set of data was obtained from 15 maps surveyed in 2000 at 1:1000 scale. Such maps were scanned, digitized, and geocorrected in AutoCAD, and then cross sections were extracted. Twelve cross sections were selected, paying attention to represent the different conditions (e.g., channel morphology, confinement) that occur in the study reach (Fig. 4). The 12 cross sections were resurveyed in October 2012 using a total station. The survey was carried out in October because flows were low and vegetation cover (i.e., leaves) does not hamper the survey. Besides, surveys in 2000 were carried out in October too.

Morphological changes were analyzed considering the following channel features: bed elevation, channel width,



Fig. 2 Channel morphology of the Lighvan River. **a** upstream reach near Section 4; **b** downstream reach near Section 12

channel depth, and cross-sectional area. As for bed elevation, the thalweg was considered, i.e., the lowest point within the channel. For comparison of cross sections, an error of about 10 cm was taken into account. Cross-sectional area corresponds to bankfull area.

Hydrological analysis

To assess climate control on channel changes, rainfall series and discharge regime were analyzed, considering a time period that precedes channel changes (i.e., 2000–2012). Monthly precipitation and annual peak discharges were analyzed at Lighvan and Heravi stations from 1991 to 2012. Two time spans were considered in such analyses, specifically 1991–2000 and 2001–2012.

Land-use changes and effects on runoff and peak discharge

Land-use changes were analyzed to assess possible implications on channel processes and, more specifically, effects

on runoff. Landsat ETM + images, respectively, of 2000 and 2012, were used to analyze land use at catchment scale. Such images have a spatial resolution of 30×30 m. The analysis was carried out using ENVI 4.7 and a supervised classification. The following land-use classes were defined: garden, irrigated farming, rainfed farming, bare land, residential areas, dense pasture, and weak pasture. Training data were acquired by field survey (using GPS), Google Earth images, and previous land-use maps. Supervised classification was obtained using the maximum likelihood algorithm. Several studies have estimated the effect of land-use changes on runoff (e.g., Shi et al. 2007; Wijesekara et al. 2010; Ali et al. 2011).

The aim was to assess the effect of land-use changes on peak discharge in the Lighvan catchment. Lighvan catchment was divided into 12 sub-catchments based on 12 cross sections. Then the peak discharges were estimated by SCS method for 12 cross sections in 2000 and 2012. SCS method has been presented by Soil Conservation Services for estimating flood discharge using rainfall and characteristics of watersheds.

According to this method, if the precipitation occurs on a basin with duration (T) and concentration time T_c , the time that discharge reaches to peak is T_p according to the following equation:

$$T_p = 0.6T_c + \sqrt{T_c} \quad (1)$$

The concentration time is determined using Kirpich formula (Kirpich 1940; Natural Resources Conservation Service 2008; Vahabzadeh et al. 2013) that is used in this study because of the ease measurement of parameters and acceptable accuracy.

$$T_c = \frac{0.0003L^{0.77}}{S^{0.385}} \quad (2)$$

where L is the length of main channel (m) and S is the average slope of main channel.

Soil Conservation Service has offered the following formula for estimating peak discharge (Q_p):

$$Q_p = \frac{0.0208AR}{T_p} \quad (3)$$

$$R = \frac{(P - 0.2S)^2}{P + 0.8S} \quad (4)$$

$$S = \frac{2540}{CN} - 25.4 \quad (5)$$

where A is the catchment area (hc), R is the runoff (cm), T_p is the time to reach peak discharge, S is the potential maximum retention or infiltration (cm), P is the precipitation (24 h maximum precipitation of 30 years Lighvan and Hervi stations), and CN is the curve number that depends on some factors such as hydrologic soil groups, vegetation,

Table 2 Changes in channel morphology over the period 2000–2012

Cross section	Year	Bed elevation (m_a.s.l)	Bed elevation changes (m)	Channel width (m)	Width changes (m)	Width changes %	Average depth (m)	Average depth changes (m)	Cross-sectional area (m ²)	Cross-sectional changes %	Morphological changes
1	2000	2246.05	0.3	9.8	-0.84	-9	0.4	-0.2	3.92	-54	Aggradation/ Narrowing
	2012	2246.31		9			0.2		1.8		
2	2000	2198.31	0.8	11.9	-0.8	-6	0.89	-0.24	10.54	-31	Aggradation/ Narrowing
	2012	2199.07		11.1			0.65		7.26		
3	2000	2156.02	-	19	-4	-22	0.43	-0.18	8.23	-56	n.s.c ^a / Narrowing
	2012	2156.01		14.7			0.25		3.65		
4	2000	2134.19	-0.6	13.9	-5.6	-40	0.58	0.12	8.08	-28	Incision/ Narrowing
	2012	2133.57		8.3			0.7		5.8		
5	2000	2107.44	0.5	5.7	-1.4	-24	0.38	-0.12	2.17	-48	Aggradation/ Narrowing
	2012	2107.92		4.4			0.26		1.12		
6	2000	2060.89	-0.7	10.8	-5.3	-49	0.83	0.09	8.96	-44	Incision/ Narrowing
	2012	2060.14		5.5			0.92		5.06		
7	2000	2035.22	-	9.2	-1.8	-19	0.85	-0.4	7.78	-57	n.s.c/ Narrowing
	2012	2035.27		7.6			0.45		3.32		
8	2000	2018.2	-0.9	13.5	-1.3	-9	0.6	0.41	8.03	54	Incision/ Narrowing
	2012	2017.26		12.2			1.01		12.4		
9	2000	1993.2	-1	6.3	3.7	60	0.28	0.74	1.74	483	Incision/ Widening
	2012	1992.19		10			1.02		10.15		
10	2000	1954.93	-0.2	8.9	6.5	73	0.44	0.27	3.92	179	Incision/ Widening
	2012	1954.76		15.3			0.71		10.95		
11	2000	1950.62	-0.4	9.6	-	-	0.76	-0.2	7.31	-26	Incision/n.s.c.
	2012	1950.26		9.6			0.56		5.4		
12	2000	1897.91	-0.2	35.7	-18.2	-51	0.81	-0.35	28.81	-80	Incision/ Narrowing
	2012	1897.7		17.6			0.46		5.62		

See Fig. 4 for cross sections' location

^a No significant change



Fig. 3 Channelization (a) and bank protection structures (b) along the Lighvan River

and watershed land use (Chow 1988). CN value in SCS model describes the relationship between rainfall and runoff, which reflects the runoff generation capability of underlying surface unit in a basin (Alizadeh 2007).

After calculating all of parameters such as T_c , T_p , CN, S , and Q_p for 12 sub-catchments, then unit stream power was estimated for the 12 sections in 2000 and 2012.

Stream power represents the rate of doing work (in transporting water and sediment), which is the potential for flowing water to perform geomorphic work. Unit stream power (ω), the stream power per unit bed area, is defined as

$$\omega = \frac{\rho g QS}{W} \quad (6)$$

where Q is the discharge ($\text{m}^3 \text{s}^{-1}$), W is the channel width (m), S is the longitudinal slope (m m^{-1}), ρ is the fluid density (kg m^{-3}), and g is the acceleration due to gravity (m s^{-2}) (Petit et al. 2005; Knighton 1999).



Fig. 4 Location of the twelve cross sections analyzed in this study

Results

Channel changes

Channel changes over the period 2000–2012 were investigated by comparison of 12 cross sections (Fig. 5). Bed elevation has decreased in seven cross sections and increased in three out of twelve (Fig. 6). In two Sections (3 and 7), no significant changes occurred (Table 2). Aggradation was the dominant process in the upstream part of the study reach (Section 1, 2, and 5), where was on average 0.5 m. Incision was dominant in the middle and lower part of the study reach, varying between 0.2 and 1.0 m and being on average 0.6 m (Fig. 6; Table 2). Channel width has decreased in all the cross sections except three (Table 2). Narrowing ranged between 0.8 m and 18.2 m (i.e., between 6 % and 51 %), while widening took place just in Sections 9 and 10, but it was intense, respectively, 60 and 73 %.

Looking to the overall change of these cross sections, it comes out that cross-sectional area decreased in 9 sections in response to narrowing associated with aggradation or

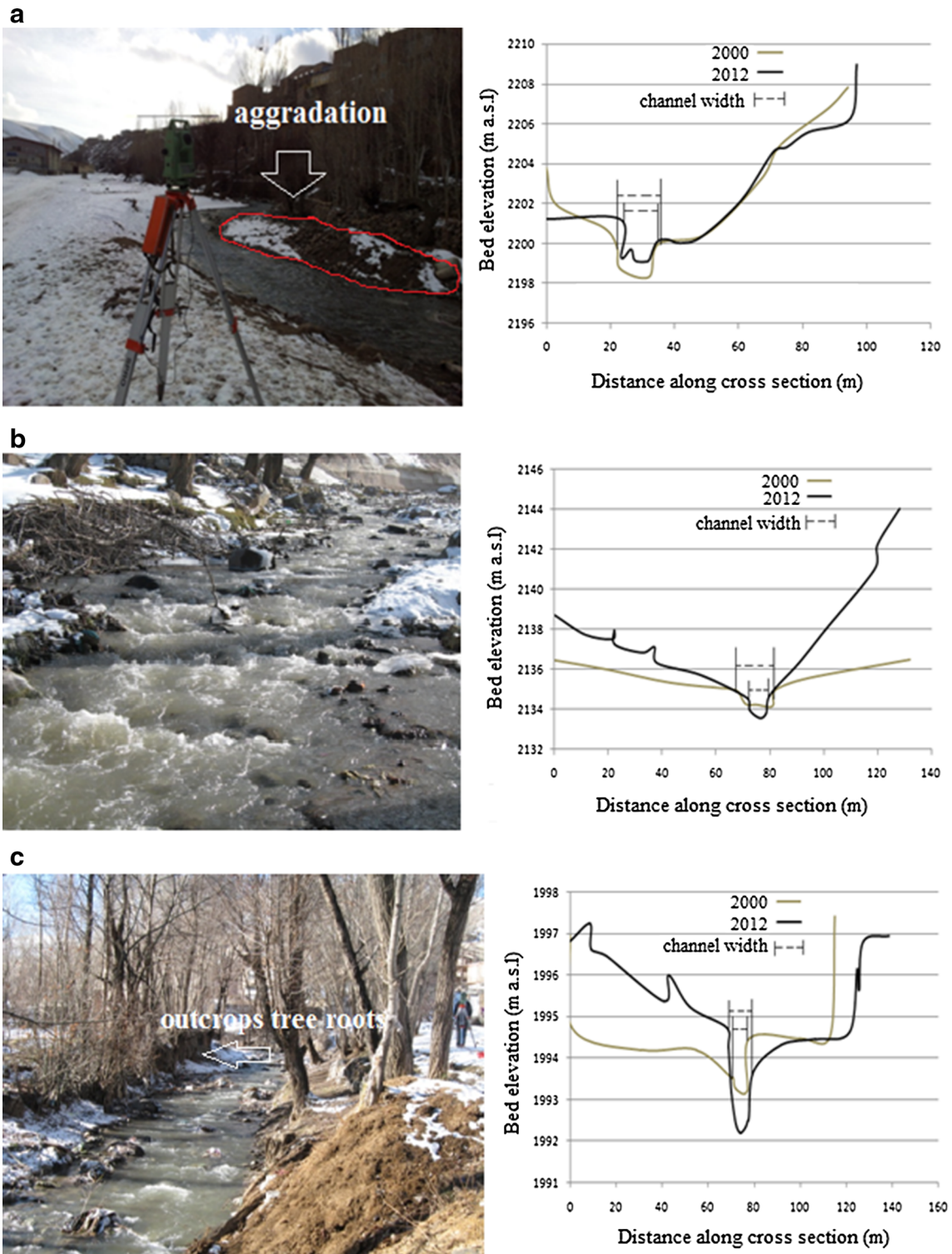


Fig. 5 Examples of cross section comparison: **a** cross section 2 (*aggradation* and *narrowing*); **b** cross section 4 (*incision* and *narrowing*); **c** cross section 9 (*incision* and *widening*)

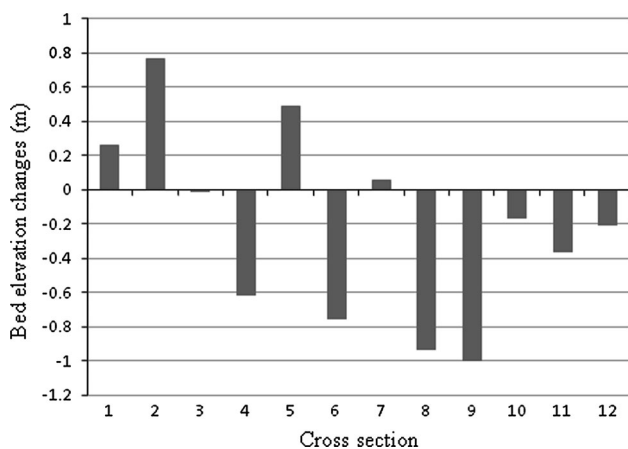


Fig. 6 Bed-level changes in the twelve cross sections over the period 2000–2012

incision (Table 2; Fig. 5a, b). Cross-sectional area increased in the other 3 sections, in particular in Sections 9 and 10, where widening was associated with incision (Fig. 5c).

Hydrological analysis

Figure 7 represents average monthly precipitation over the periods 1991–2000 and 2001–2012 in the Lighvan catchment. Comparison of the two periods points out that precipitation was higher in the second period (i.e., 2001–2012) both considering total annual precipitation and average monthly precipitation.

The annual peak discharges at Lighvan and Hervi gaging stations are shown in Fig. 8. The average annual peak discharges at Lighvan station were 6.6 and 8.7 m³/s in the period 1991–2000 and 2001–2012, respectively. Also, at Hervi station, the average annual peak discharge shows some increase, from 14.1 m³/s in 1991–2000 to 15.5 m³/s in 2001–2012, although lower than in the Lighvan station

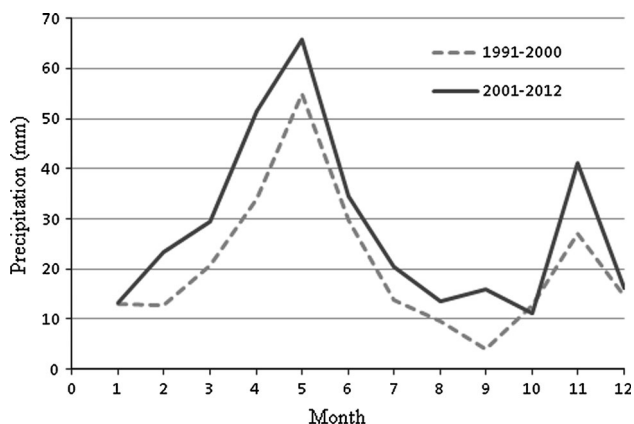


Fig. 7 Average monthly precipitation in the Lighvan catchment in the periods 1991–2000 and 2001–2012

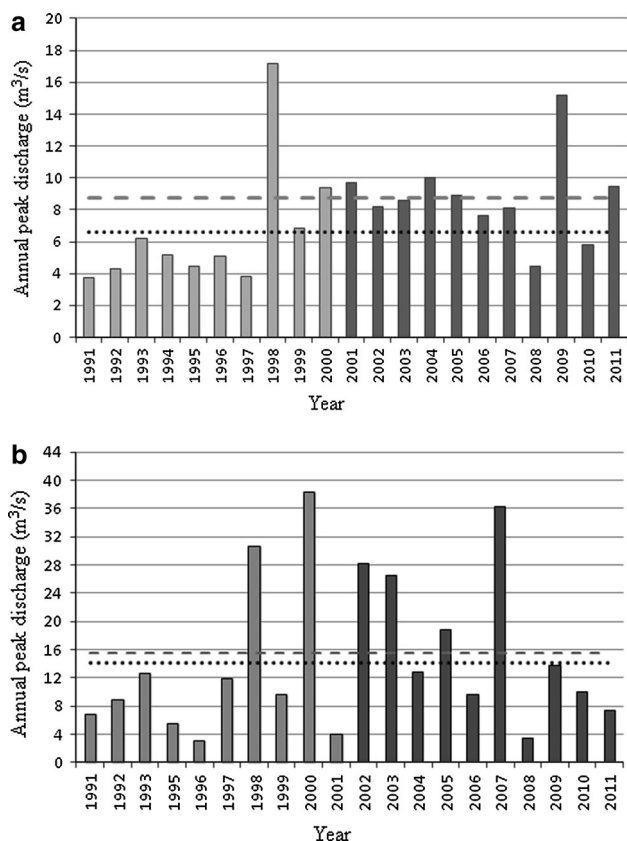


Fig. 8 Annual peak discharges pre- and post-2000 with their respective mean discharge values (post-2000: dashed line, pre-2000: dotted line). **a** Lighvan station; **b** Hervi station; see Fig. 1 for location of the gaging stations

(Fig. 8). In some years, that peak flow was higher upstream than downstream because according to hydrologic soil groups, most of upstream catchment is made mainly of C type, while the downstream catchment is of A type. Permeability of A is higher than C. Also rainfall in upper catchment is higher than in the lower catchment.

Land-use changes and effects on runoff

Land-use maps were carried out for 2000 and 2012 using seven classes (Fig. 9). Changes in land use are reported in Table 3. Notable changes occurred between 2000 and 2012: decreasing of dense pasture (−44 %) and bare land (−54.3 %) and increasing of residential area (88.9 %), weak pasture (45.5 %), rainfed farming (38.6 %). Therefore, land use in this semi-arid region undergone substantial change in short time period (2000–2012), as shown also by Mallick et al. (2014), and it was mainly controlled by human rather than natural factors.

As described in the previous section, peak discharges were calculated using SCS method. Using data from land-use maps, hydrologic soil groups of study area (A, B, and C), the curve number (CN) was calculated. The 75.87

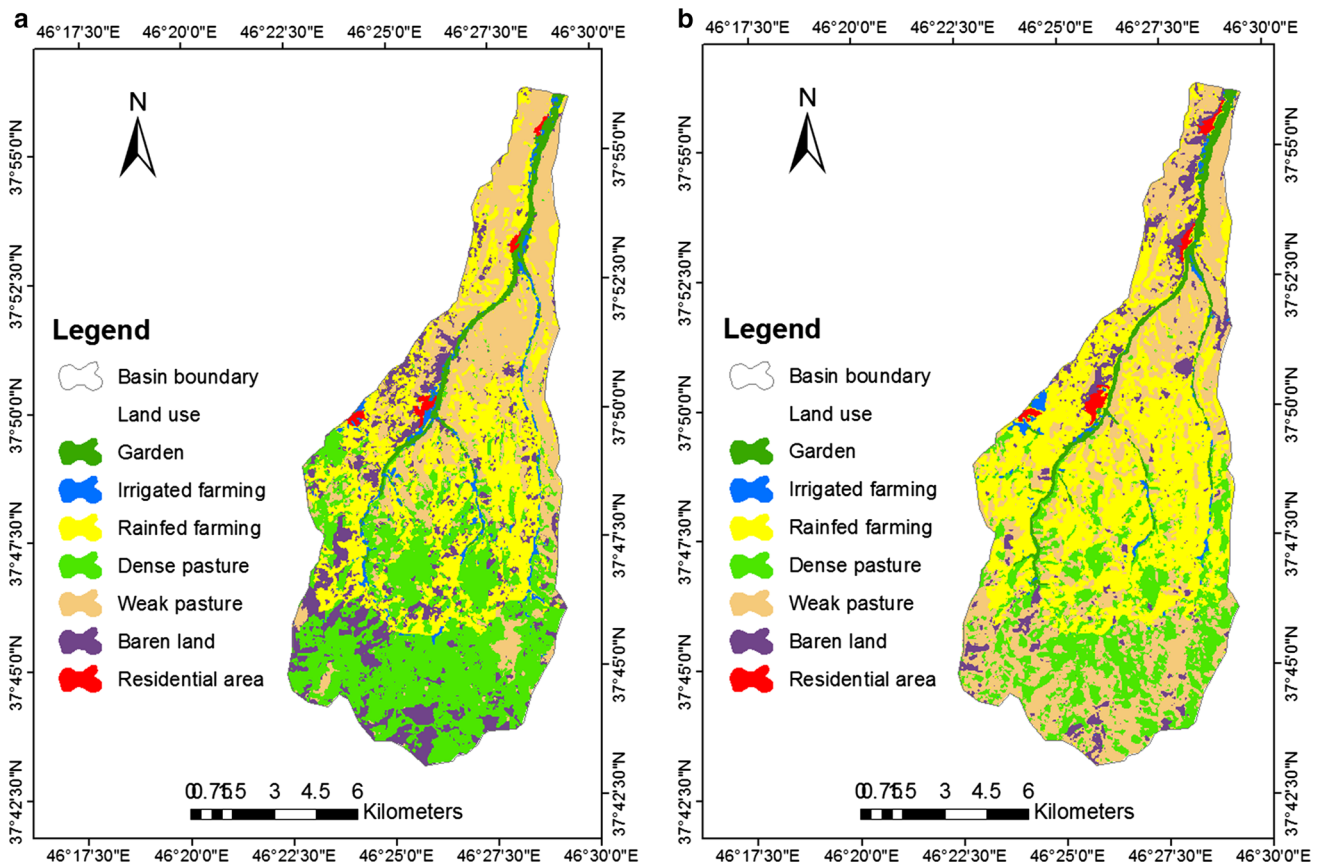


Fig. 9 Land use in the Lighvan catchment in 2000 (a) and 2012 (b) obtained from supervised classification of Landsat images

Table 3 Land use in 2000 and 2012 and changes between the two dates

Land use	2000		2012		Change %
	Area (km ²)	Area (%)	Area (km ²)	Area (%)	
Residential area	0.9	0.6	1.7	1.1	88.9
Garden	3.9	2.8	5	3.6	28.2
Irrigated farming	3.2	2.2	1.5	1	−0.5
Rainfed farming	37.5	26.5	52	36.7	38.6
Dense pasture	44.7	31.5	25	17.6	−44
Weak pasture	33.2	23.4	48.3	34	45.5
Bare land	18.6	13	8.5	6	−54.3
Sum	142	100	142	100	–

percent of the Lighvan catchment has type C that has low infiltration, and it can create high runoff. So CN has increased from 2000 to 2012 in all of cross sections due to land-use changes. The larger the CN value is, the larger the runoff volume will be under certain underlying surface units. Also the potential maximum retention (S) is determined based on curve number that also has increased in all sections (Table 4). Then runoff with different returns periods is based on potential maximum retention and 24 h maximum precipitation. Table 4 shows that runoff has

increased in sub-basins in different return periods from 2000 to 2012 because land-use changes occurred between 2000 and 2012 (Table 3) that has been increased curve number. Therefore, land-use changes have caused runoff increasing.

Finally, peak discharge was calculated (see in Table 5) according to 12 cross sections, the runoff, and the time to reach peak discharge. Such estimates show that land-use changes had significant effects on peak discharges in all cross sections.

Table 4 CN, S Runoff estimated by SCS method

Cross section	Year	CN	S	Runoff (mm), for different RI			
				2 year	5 year	10 year	25 year
1	2000	75.32	8.32	0.8	3	5.2	8.4
	2012	75.31	8.33	0.8	3	5.2	8.4
2	2000	76.93	7.61	1.1	3.8	6.2	9.7
	2012	77.18	7.51	1.2	3.9	6.3	9.9
3	2000	76.86	7.65	1	3.9	6.6	10.7
	2012	77.21	7.50	1.1	4.1	6.8	11
4	2000	76.92	7.62	1	3.9	6.6	10.8
	2012	77.34	7.44	1.1	4.1	6.9	11.2
5	2000	76.24	7.91	0.9	3.6	6.2	10.2
	2012	76.82	7.66	1	3.9	6.8	10.7
6	2000	75.43	8.27	0.7	3.2	5.7	9.6
	2012	76.10	7.97	0.6	3.5	6.1	10.1
7	2000	74.89	8.52	0.6	3	5.38	9.12
	2012	75.56	8.21	0.8	3.3	5.8	9.7
8	2000	74.73	8.59	0.6	2.9	5.3	9
	2012	75.45	8.26	0.7	3.2	5.7	9.57
9	2000	74.59	8.65	0.5	3	5.7	10
	2012	75.37	8.29	0.65	3.34	6.1	10.6
10	2000	73.91	8.97	0.4	2.7	5.3	9.4
	2012	74.37	8.75	0.5	2.9	5.5	9.8
11	2000	73.63	9.1	0.38	2.62	5.10	9.19
	2012	74.42	8.73	0.5	2.9	5.6	9.8
12	2000	72.90	9.44	0.3	2.4	4.7	8.6
	2012	73.8	9.02	0.8	2.7	5.2	9.3

4–4 Changes in unit stream power

Unit stream power was calculated for each cross section considering channel morphology, especially channel width, in 2000 and 2012 (Table 6). Besides, calculations were carried out for floods of different magnitudes (i.e., recurrence intervals equal 2, 5, 10, and 25 years). Unit stream power has increased during 2000–2012 in most of the cross sections (10 out of 12) because peak discharge has commonly increased (Table 5) and channel width has decreased in most of the cross sections (Table 2).

Discussion and final remarks

In order to explain the morphological changes that took place along the Lighvan River in the short term, it is needed to link those changes with driving factors. Here, it is discussed the possible role played by human and natural factors.

Magnitude of annual peak discharges increased over the period 1991–2012 (Fig. 8), and it can be suggested that such increase is related to natural causes (i.e., increase of precipitation, see Fig. 7). On the other hand, the analysis

concerning land use at catchment scale has shown that notable changes occurred in the Lighvan catchment in the period 2000–2012 (Table 3) and that such changes had some effects on runoff and formative discharges. It is likely that changes in land use had effects also on sediment fluxes. Specifically, it would be worth to analyze if production of coarse material has increased at catchment scale, and, therefore, if bedload transport has increased along the Lighvan River, but the available data do not allow such analysis. On the other hand, there is a clear evidence of several human interventions that directly affected channel morphology. Increase of human activities in the catchment and along the main river (e.g., construction of new houses and roads, increase of farming) has been associated to channelization works in several portions of the river. Channelization was aimed to reduce flood risk and to control bank erosion. Some of the observed changes in channel width are clearly due to channelization works (e.g., Sections 8 and 12) (Fig. 3). Channelization involved channel narrowing and lowering of the streambed by dredging. Incision was due to dredging, but also to increase in unit stream power which was notable at some cross sections (e.g., Section 12) (Table 6).

Table 5 Peak discharges estimated by SCS method

Cross section	Area (km ²)	T _p (hr)	Year	Peak discharge (m ³ /s) for different RI			
				2 year	5 year	10 year	25 year
1	2.58	1.67	2000	5.6	22.2	37.7	61
			2012	5.6	22.1	37.5	60.8
2	76.5	1.84	2000	9.8	32.7	53.2	83.5
			2012	10.3	33.7	54.1	85.3
3	80.3	1.98	2000	8.6	32.8	55.6	90.6
			2012	9.3	34.3	57.6	93.2
4	85.2	2.05	2000	9	33.9	57.4	93.3
			2012	9.8	35.7	59.8	96.5
5	88	2.15	2000	7.7	30.6	52.8	87
			2012	8.6	33	55.9	91.2
6	91.2	2.32	2000	6	26.5	46.6	78.1
			2012	5	28.9	50	82.6
7	93.6	2.42	2000	5.05	24.2	43.3	73.4
			2012	6.05	26.5	46.5	77.7
8	94.2	2.49	2000	4.7	23.11	41.58	70.75
			2012	5.8	25.5	44.9	72.3
9	127.8	2.58	2000	5.3	31	58.2	102.5
			2012	6.7	34.4	63.1	109.3
10	130.9	2.74	2000	4.2	27.2	52.2	93.4
			2012	4.8	29	54.9	97.1
11	135.6	2.76	2000	3.9	26.8	52.1	93.9
			2012	5	30	56.7	100.3
12	140.4	3	2000	2.8	22.9	45.7	84
			2012	3.9	26.2	50.5	90.7

A first conclusion about driving factors is that both human and natural factors had a role in the recent evolution of the Lighvan River. Channelization and increase of peak discharges (due to an increase of precipitation and land-use changes) have been the main drivers of channel evolution. Following this conclusion, it is useful to consider if the observed morphological changes are those expected for these types of change in driving variables (i.e., discharge) and boundary conditions, for instance, it can be referred to Schumm’s empirical equation (1969) that provides direction of channel response to changes in a driving variable:

$$Q^+ = w^+, d^+, w/d^+, \lambda^+, s^-$$

where Q is the discharge, w is the width, d is the mean depth, λ is the meander wavelength, and s is the channel gradient, using a + or – to denote an increase or decrease on channel form variables. As expected, the channel has increased its depth (i.e., incised) in most of the cross sections (Fig. 6), while widening has occurred only in few sections (i.e., n. 9 and 10, see Table 2) due to the absence of channelization works. Specifically, cross sections 9 and 10 are located in a rural area, downstream of a channelized (cross sections 8) and urbanized reach (Beyragh Village).

Therefore, channel response is coherent with existing model (e.g., Lane 1955; Schumm 1969) although explanation of channel response is not always straightforward because complex interaction of different factors in the Lighvan fluvial system. Understanding of channel changes, and their causes, could be improved by further investigations (e.g., about sediment sources and dynamics in this fluvial system).

Calculations of changes in unit stream power provide some additional insights about channel evolution. The fact that unit stream power has increased in 10 cross sections out of 12 suggests that further channel adjustments could occur in the near future. As mentioned above, lacking of information about sediment fluxes makes prediction quite difficult but, according to recent adjustments (2000–2012), further incision could be expected in those reaches where there are bank protections, while further widening in those reaches (e.g., cross sections 9 and 10), where bank erosion is not prevented.

Analyses of channel changes and understanding the causes of changes have important practical implications. First, if channel incision is going to continue in the Lighvan River, there could be negative effects on structures

Table 6 Unit stream power in different dates (2000 and 2012)

Cross section	Recurrence interval (year)	Unit stream power in 2000 (Wm^{-2})	Unit stream power in 2012 (Wm^{-2})	Unit stream power in 2012/Unit stream power in 2000
1	2	566	615	1.08
	5	2224	2423	1.09
	10	3765	4105	1.09
	25	6099	6655	1.09
2	2	747	841	1.13
	5	2506	2763	1.10
	10	4073	4465	1.10
	25	6399	6985	1.09
3	2	383	533	1.39
	5	1456	1961	1.35
	10	2468	3294	1.33
	25	4021	5331	1.32
4	2	525	966	1.84
	5	1986	3510	1.77
	10	3361	5879	1.75
	25	5470	9493	1.73
5	2	1022	1533	1.50
	5	4139	5851	1.41
	10	7129	9927	1.39
	25	11754	16187	1.38
6	2	402	924	2.30
	5	1788	3803	2.13
	10	3149	6574	2.09
	25	5279	10869	2.06
7	2	385	561	1.46
	5	1842	2458	1.33
	10	3299	43139	1.31
	25	55949	72109	1.29
8	2	237	317	1.34
	5	1158	1410	1.22
	10	2084	2482	1.19
	25	3546	4159	1.17
9	2	560	439	0.78
	5	3249	2264	0.70
	10	6104	4149	0.68
	25	10755	7186	0.67
10	2	293.96	197.33	0.67
	5	1919	1186	0.62
	10	3691	2244	0.61
	25	6607	3974	0.60
11	2	249	325	1.30
	5	1718	1937	1.13
	10	3336	3660	1.10
	25	6012	6473	1.08

Table 6 continued

Cross section	Recurrence interval (year)	Unit stream power in 2000 (Wm^{-2})	Unit stream power in 2012 (Wm^{-2})	Unit stream power in 2012/Unit stream power in 2000
12	2	45	127	2.81
	5	365	847	2.32
	10	728	1636	2.24
	25	1337	2936	2.20

(e.g., bank protection structures, walls). Second, cross-sectional areas have commonly decreased along the river (Table 2), causing an overall increase of flood risk (i.e., probability of inundation of the floodplain). This suggests that river management could not rely only on channelization, and other solutions should be identified to prevent negative effects of channel instability in the near future.

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