Research papers

Effects of hydrological events on morphological evolution of a fluvial system

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ABSTRACT

This study quantifies morphological evolution of the Dez River, Iran, from 1955 to 2016. The approach uses a sequence of Landsat images, aerial photos, and topographic maps. In addition, the hydrological data including average daily discharge and yearly maximum discharge at the Dezful hydrological station for the period (1955–2016) were used. The study reach was divided into 48 meander loops from upstream to downstream. Active channel width (w) was determined at 10 m intervals and changes assessed along the study reach of the Dez River. Morphological indices including sinuosity index; straight meander length; centerline flow length; erosion area; erodible length channel migration; centerline elongation; and radius of curvature were calculated in the reach. Results showed that the study reach of the Dez River changed dramatically in response to major floods, although the general trend is towards a narrowing of active channel width by 38% in the period 1955–2016. Results show that most of the meander loops in the study area extended and expanded. Between 1989 and 1995, all types of meander change were observed. There was a direct correlation between the frequency of hydrological events (flood days) bigger than 2-years return period and elongation of bends.

1. Introduction

Rivers represent an important and dynamic landscape feature in the world's great plains and valleys. Fluvial systems in these regions are, however, under threat, coming under increasing pressure from growing populations and the demand placed on water, particularly in drier zones. River systems are used as a source of energy, food, transport and subjected to geopolitics (Surian and Rinaldi, 2003; Yousefi et al., 2017a). Fluvial ecosystems are among the most threatened ecosystems in the world, where pollution, urbanization, bio-invasion or changes in water regime results in degraded landscapes (Das et al., 2014; Luppi et al., 2009a; Thakur et al., 2012).

Change in river morphology results in adjustment of other morphological and ecological characteristics until the river adapts to the new conditions (Camporeale and Ridolfi, 2010; Chu et al., 2006; Csiki and Rhoads, 2014; Engel and Rhoads, 2012; Keesstra et al., 2005; Rhoads et al., 2016; Yousefi et al., 2017a). Morphological evolution of large floodplain rivers has been attributed to direct human intervention (e.g. water abstraction, regulation, dams, bridges, sand mining, and

river protection activities) as well as indirect impacts (e.g. land use change, climate change, and population growth) (Camporeale and Ridolfi, 2010; Demir and Hasdemir, 2005; Keesstra et al., 2005; Lofthouse and Robert, 2008; Perucca et al., 2006; Spitz et al., 2001; Yousefi et al., 2017b, 2015b; Zhang et al., 2008). Natural processes are also important (e.g. Gilvear et al., 2000; Hudson and Kesel, 2000). River reach morphologies are an assemblage of hydro-geomorphological forms, and large hydrological events are the most important driving forces of change in these fluvial systems and their parameters (Camporeale and Ridolfi, 2010; Dépret et al., 2015). These changes in river parameters over time need to be considered for urban planning, dam and road construction, erosion and sedimentation (Csiki and Rhoads, 2014; Gordon and Meentemeyer, 2006; Gregory, 2006; Kiss and Blanka, 2012; Kondolf et al., 2007; Ma et al., 2012; Nelson et al., 2013; Vadnais et al., 2012; Yanan et al., 2011).

Many studies have contributed to the relationship between hydrology and fluvial geomorphology (e.g. Peixoto et al., 2009; Camporeale and Ridolfi, 2010; Dépret et al., 2015, 2017; Hooke, 2016), often focusing on the impact of discrete large flood events (e.g. Phillips

2002; Fuller, 2008; Hauer and Habersack, 2009; Milan, 2012; Thompson and Croke, 2013). Fewer studies to date have specifically investigated the frequency of floods on channel morphology (Dépret et al., 2015). Phillips (2002) indicated that flash floods in a forested headwater basin, with recurrence interval (RI) flows > 200 years, were the only floods to cause significant channel change in ∼20 years. In contrast, Dean and Schmidt (2013) found that a flood in the Rio Grande with RI 13–15-years had significant effects on channel widening, up to 52%. Dépret et al. (2015) considered the hydrological control on the morphogenesis of low-energy meanders in Cher River, France. They examined the duration, frequency, and intensity of floods on the changes in the river morphology and demonstrated that the river morphology was controlled by low-magnitude hydrological events. However, in a study Hooke (2016b) investigating the morphological impacts of flow events of varying magnitude on ephemeral channels in a semiarid region the opposite was found, as low flows could move sediment load without significantly changing fluvial morphology. Therefore, it is important to assess the effects of hydrology on river evolution; especially the effects of extreme hydrological events on river morphology in a semi-arid climatic setting.

This research has two main aims; i) to quantity of morphological evolution of the Dez River during a ∼60 year period 1955–2016, and; ii) to assess the role of hydrological event frequency on morphological evolution in a study reach of the Dez River. An understanding of the relationship between flood events and fluvial morphological indexes could be very useful for better management of fluvial systems by watershed managers, urban planners and ecosystem services.

2. Material and methods

2.1. Study area

The Dez River (Fig. 1) has an average daily discharge of 230 m³ s⁻¹ and is a tributary of the Karoon River, which is one of the major rivers in south-west Iran. The area of the Dez Basin is about 17,320 km² and the whole length of the river is approximately 400 km (Woodbridge et al., 2016). The uplands and headwaters of the Dez River comprise the Zagros Mountains which have a maximum elevation of 4,548 m.a.s.l; in Band-e-Qir confluence the Dez River joins the Karoon River, which in turn discharges into the Arvanrood River in Khoramshahr City (elevation 12 m.a.s.l) (Salarijazi, 2012; Yousefi et al., 2016). The Dez Basin has a large range of elevations and climatic belts, but it is mainly located in a semiarid climate zone (Nourani and Mano, 2007; Salarijazi, 2012; Yousefi et al., 2016). The study area selected is a 153 km long alluvial deposition reach of the Dez River, located in southern Iran (Fig. 1). The study reach is characterized by a meandering planform with a slope of 0.0261%. The upstream limit of the study reach is located near Shush City, downstream of the Dez Dam that was constructed in 1956. According to the floodplain of the study reach a 1 km buffer area was defined along the study reach to monitor more spatial changes by using the topographic maps and Arc GIS 4.2 software.

2.2. Data used

Landsat images, aerial photos, and topographic maps were used to analyze changes in the river morphology in response to hydrological events (Table 1). The hydrological data including average daily discharge and yearly maximum discharge at the Dezful hydrological station for long period (1955–2016) were analyzed. The Dezful station is the nearest hydrological station to the study reach, located about 10 km upstream of the study reach itself (Fig. 1), no significant tributaries join the Dez River between the gauging station and the study reach, nor along the 153 km long study reach. Change in flow along the study reach is therefore not thought to be significant. However, this is an uncertainty for the present study.

Geometric corrections were applied on the aerial photos of 1955

according to 27 ground control points in stable parts of vector roads and residential places in Dezful and Shush cities, also in Band-e-Qir. A geometric correction of these photos was done with a non-parametric polynomial method by ArcGIS 10.2. The total error of corrections was estimated according to root mean standard error (RMSE), and gives 1.78 m in pixel (Giriraj et al., 2008; Yousefi et al., 2015b). Using true composite images in Landsat data (Red, Green, and Blue bands) and normalized difference water index (NDWI), the active channel for study periods by ENVI 4.8 was extracted (Haibo et al., 2011; Ko et al., 2015; Yousefi et al., 2015a).

Based on 2016 Landsat OLI image, the study reach was divided into 48 meander loops. Using Fluvial Corridor 10.1, the active channel width (w) was determined in 10 m intervals and changes were detected along the entire 153 km reach of the Dez River (Roux et al., 2015; Yousefi et al., 2016). In addition, the sinuosity index (Eq. (1)), straight meander length (L), centerline flow length (S), erosion area (EA), erodible length (EL), channel migration (M); (Eq. (2), centerline elongation (E), and radius of curvature (Rc), were calculated to provide morphological indices (Grenfell et al., 2014; Hooke, 2013; Yousefi et al., 2015b).

$$S = C/L \tag{1}$$

where S is sinuosity, C is channel length and L is straight-line valley length between measurement points

$$M = \left(\frac{\sum EA}{\sum EL} \right) / T \tag{2}$$

where: M is migration rate, T is the duration of period in year, EA is erosion area and EL is erosion length.

To identify meander evolution there are various classes and models, while most of this methods derived from case studies (Güneralp et al., 2012; Güneralp and Rhoads, 2009; Luppi et al., 2009b; Peixoto et al., 2009; Van De Wiel et al., 2011). In the current study, meander loop changes and their evolution have been defined using's Hooke (1984) model (Fig. 2). This model also has been used by Yousefi et al. (2016) in the Karoon River where the model is applied to detecting morphological changes in an adjacent semi-arid meandering river into which the Dez River flows.

Using the maximum yearly discharge recorded at the Dezful Station the 2, 5, 20, 50, and 100-years recurrence interval discharges were calculated according to Log-Pearson type III distribution. In addition, using average daily discharge the frequency (number of flood days per year) of the different recurrence interval discharges was calculated for all discrete study periods (cf. Tables 1–3).

A Pearson correlation test was used to statistically analyze the relationship between the frequency of the different recurrence interval discharge in the Dezful Station and change in morphological indices (Bihamta and ZareChahouki, 2010; Dépret et al., 2015; Pfanzagl and Hamböker, 1994; Yousefi et al., 2016). Fig. 3 shows a flowchart of the methodology used in the present study.

3. Results

3.1. Geomorphological evolution

3.1.1. Width of active channel

The average width of the active channel along the 153 km study reach narrowed significantly between 1955 and 2016 by ∼70 m, or 38% (Fig. 4). The greatest reduction in width occurred in the second study period (1989–1995). The channel width totally decreased about 70 m (38%) during 1955–2016. In addition, the single most intensive reduction in active channel width occurred at meander number 22 (cf. Fig. 1), where the average active channel width for this meander reduced from 274 m in 1955 to 162 m in 2016.
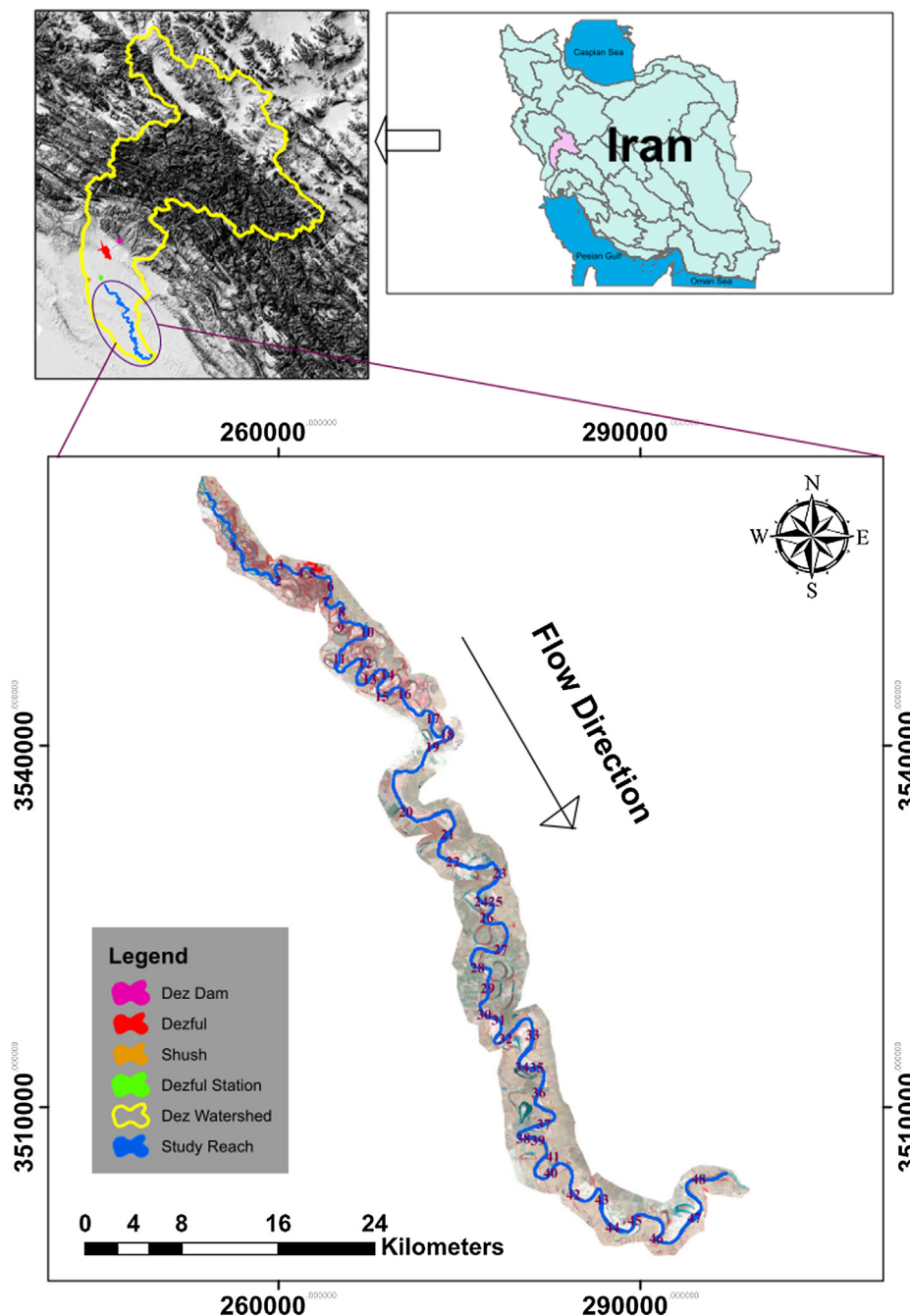
Fig. 1. Location of study area.

3.1.2. Radius of curvature

Trends in radius of curvature (Rc) of meanders in the study reach show two directions (Fig. 5). A reduction in Rc initially occurred from 1955 to 1995, before increasing from 1995 to 2016. In general, 1995 is a turning point during the study period. The largest single overall reduction in radius of curvature occurred in meander number 25, changing from 1.7 in 1955 to 0.38 in 2016.

Table 1
Data used in the study area.

| Data	Date	Scale	Provider	Use
Aerial Photo	12/June/1955	1:30000	National Cartographic Center of Iran (NCC)	Channel analysis
TM	24/May/1989	30*30 m	USGS	Channel analysis
TM	30/March/1995	30*30 m	USGS	Channel analysis
ETM +	5/June/2005	30*30 m	USGS	Channel analysis
OLI	08/May/2016	15*15 m	USGS	Channel analysis
Topography Map	25/March/2001	1:25,000	National Cartographic Center of Iran (NCC)	Geometric correction
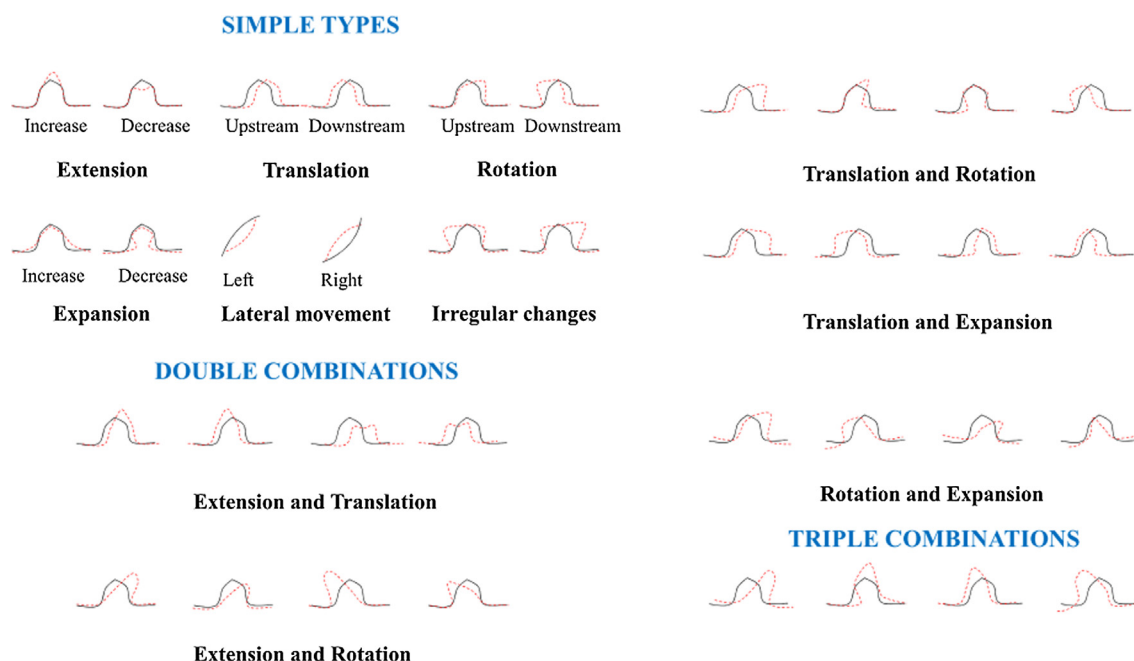
Fig. 2. Model of meander change based on Hooke (1984).

3.1.3. Sinuosity index

Results showed that the average sinuosity index during study period decreased from 2.38 to 1.91 (Fig. 6), suggesting an overall straightening of the river course. A dramatic reduction in sinuosity index occurred in the second period (1989–1995). In addition, the rate of reduction in sinuosity index reduced during the last two decades (1995–2016).

3.1.4. Channel elongation

Channel elongation in the study reach for four study periods (1955–1989, (1989–1995, 1995–2005 and 2005–2016) was calculated (Fig. 7). Results showed that the most important trend in elongation change occurred in the two periods of 1955–1989 and 1989–1995 with a reduction. However, more recently, for the periods 1995–2005 and 2005–2016 elongation has increased. In addition, the variation of elongation rate in the two first study periods (1955–1989 and 1989–1995) is more intensive than the latter two (1995–2005 and 2005–2016).

3.1.5. Channel migration

Channel migration in the study area for all study periods was calculated (Fig. 8). The greatest channel migration was observed for the second period (1989–1995) at $4.2 \, \text{m y}^{-1}$. The general trend of migration rate reduced from $2.66 \, \text{m y}^{-1}$ (1955–1989) to $1.74 \, \text{m y}^{-1}$ (2005–2016).

The meander loop changes and their evolution were classified with reference to Hooke's (1984) change model (cf. Fig. 2) (Table 2). Results show that most of the meander loops extended and expanded (a double combination change). In the second period (1989–1995), all types of

Table 3
Frequency of different recurrence interval discharges in study periods (flood day per year).

Period	Q > Q2	Q > Q5	Q > Q20	Q > Q50	Q > Q100
1955–1989	4.4	1.4	0.4	0.2	0.1
1989–1995	2.7	–	–	–	–
1995–2005	9	2.9	0.6	0.2	0.1
2005–2016	4.3	0.5	–	–	–

meander change were observed. The rarest type of meander change in the study reaches was Translation and Rotation, this kind of change was observed just for one meander (number 27) in the second period.

3.2. Hydrology and geomorphology

Fig. 9 shows the average annual discharge and the annual peak discharge during the study period. The results of Log-Pearson type III distribution show the 2-year (Q2), 5-year (Q5), 10-year (Q10), 20-year (Q20), 50-year (Q50), and 100-year (Q100) recurrence interval discharge in the Dezful gauging station, which are 285, 366, 436, 734, 1,155 and 1,725 $\text{m}^3 \text{s}^{-1}$, respectively. Table 3 shows the frequency (number of flood days per year) of different recurrence interval discharges in study periods. Results showed that just in two periods (1955–1989 and 1995–2005), floods with a magnitude of more than Q20 occurred in the study reach. As the number of hydrological events bigger than Q20 did not occur for at least three periods, we considered only the relationship between morphological evolution and Q2 and Q3
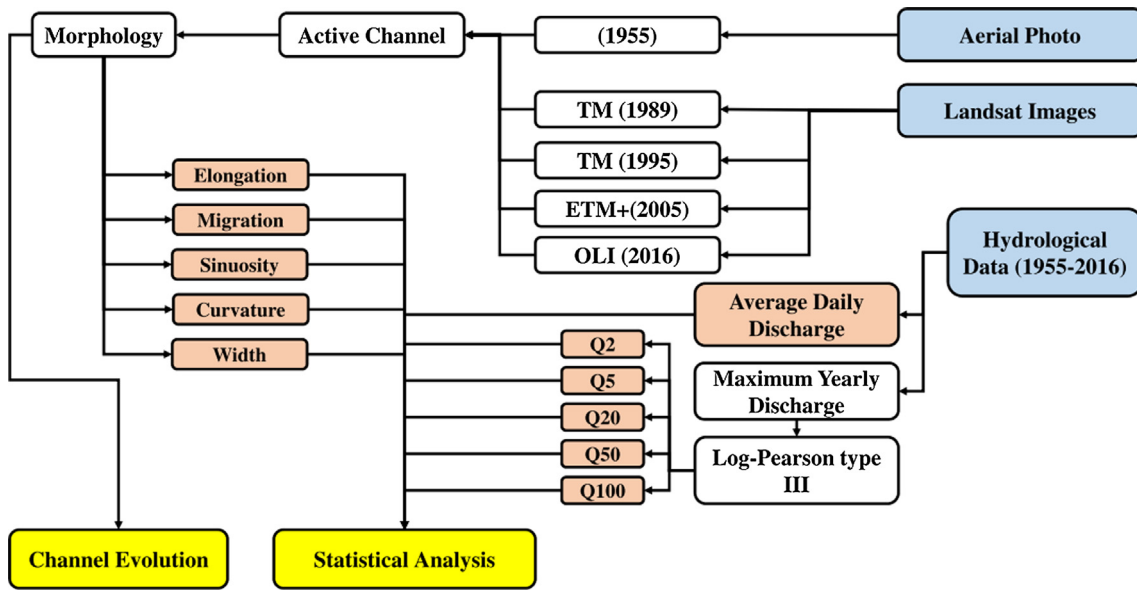
Table 2
Frequency of meanders change in different type of evolution.

Change	Simple types			Double combinations			Triple combinations		
Period	Extension	Translation	Lateral movement	Extension and Expansion	Translation and Rotation	Rotation and Expansion	Extension, Translation and Rotation	New meander	Cut off
1955–1989	2	5	–	3	–	–	–	1	2
1989–1995	4	3	2	24	1	1	1	9	4
1995–2005	4	1	7	27	–	2	2	6	1
2005–2016	1	2	3	40	–	–	–	1	–

Fig. 3. Flowchart of the used methodology.
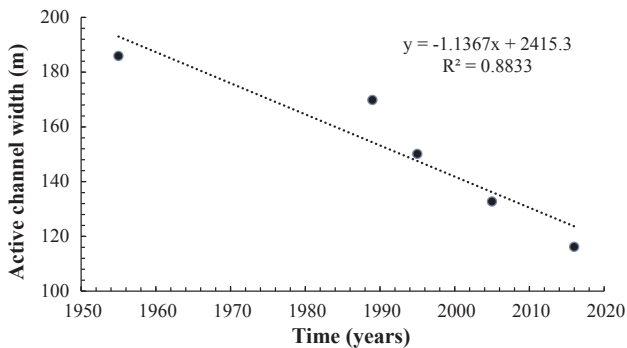
Fig. 4. Active channel width evolution and its trend.

$$y = -1.1367x + 2415.3$$
$$R^2 = 0.8833$$
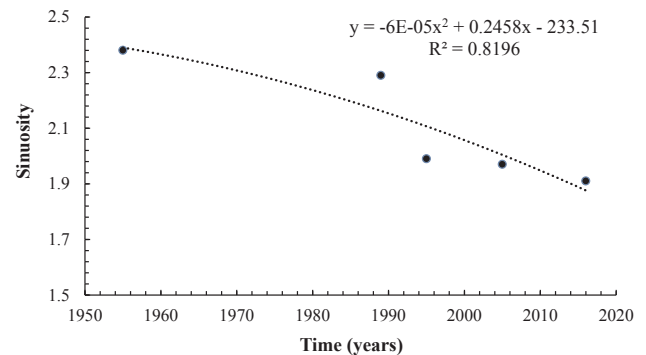
Fig. 6. Evolution of sinuosity index in study reach.

$$y = -6E\text{-}05x^2 + 0.2458x - 233.51$$
$$R^2 = 0.8196$$
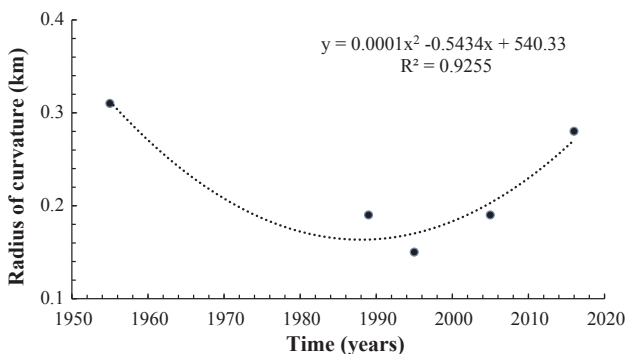
Fig. 5. Evolution of curvature radius during 1950–2016.

$$y = 0.0001x^2 - 0.5434x + 540.33$$
$$R^2 = 0.9255$$

events.

The results of a Pearson correlation test show a direct correlation between elongation and sinuosity change versus frequency of events bigger than Q2 at a 5% significant level. However, for events bigger than Q5 there is a significant correlation at 1% level with elongation, but the type of correlation is indirect. In addition, there is a direct significant correlation at the 5% level between frequency of the events bigger than Q5 and migration (Table 4 and Fig. 10). There appears to be no significant correlation between active channel width change and hydrological events of this magnitude.

4. Discussion

4.1. Geomorphological evolution

Direct and indirect driving forces can change the geomorphology of fluvial systems. In the present study, the results showed that the study reach of the Dez River changed significantly. During the entire study period, of 61 years, 17 new meanders and 7 cutoffs were created along the 153 km study reach. The active channel width reduced. No correlation was found between width and floods exceeding Q2 or Q5, suggesting that width change is in response to human activities in the channel (Hooke, 2016; Latapie et al., 2014; Ollero, 2010; Toone et al., 2014). Both sides of the Dez river have seen an increase in the area used by agriculture and the riparian vegetation has mostly been removed during recent decades. The sinuosity index suggested a reduction in sinuosity (straightening) during the ∼60 year study period, which also appeared to be correlated with smaller flood frequency (see below), but may also reflect direct human intervention in the channel with flood-plain development. Radius of curvature changed during the last ∼60 years in the study reach, but with no clear direction. However, lower Rc values recorded in 1989, 1995 and 2005 were coincident with (or immediately followed) the three largest floods in the gauged record (cf. Fig. 9), suggesting bends may have been, on average, smaller, possibly associated with cutoffs in response to these larger floods. The larger radius of curvature values recorded in 1955 and 2016 may reflect discrete bend development. The elongation assessment detected the
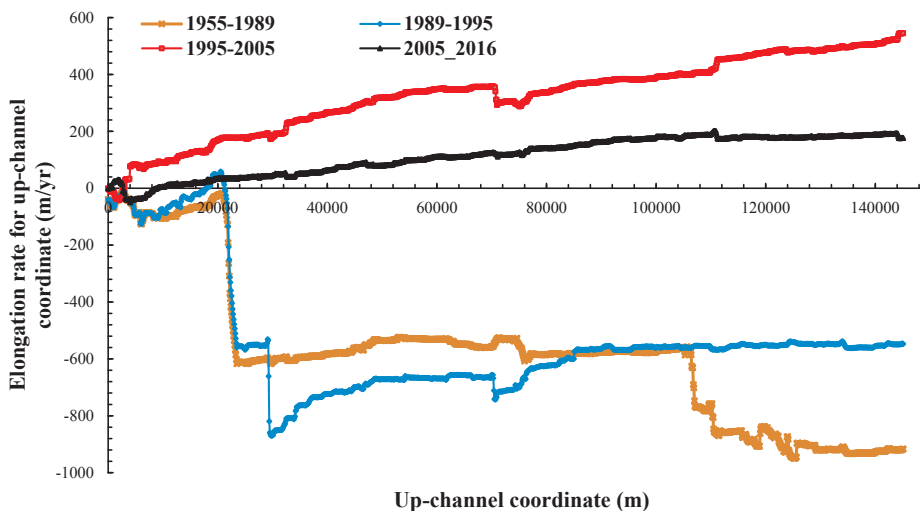
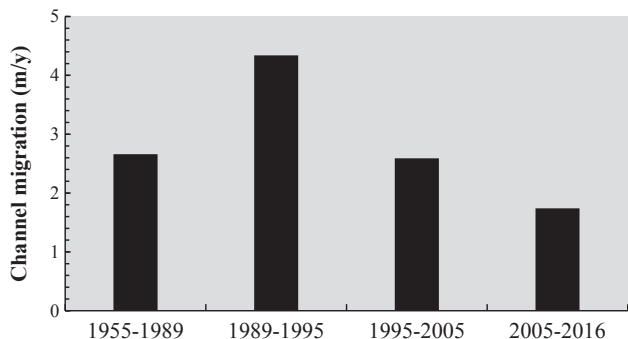**Fig. 7.** Elongation of study reach during four periods.

Fig. 8. Channel migration during four periods in study area.

Table 4
Results of Pearson correlation test between frequency of hydrological events and geomorphological evolution.

Correlation		Elongation	Migration	Sinuosity	Width
Q > Q2	Pearson correlation	0.909	−0.403	0.913	0.184
	Significant	0.046[*]	0.299	0.024[*]	0.408
Q > Q5	Pearson correlation	−0.92	0.902	0.093	0.082
	Significant	0.001[**]	0.045[*]	0.470	0.472

[*] Significant at 5% confidence level.
[**] Significant at 1% confidence level.

location of cutoffs and meander evolution. Fig. 7 shows that the variation of elongation rate in two first periods is more than the two last periods. In addition, the number of cutoffs in the first two periods exceeds the number in the last two periods. These variations in elongation and cutoffs may reflect hydrological variability in this period (Fig. 9). Once a cutoff occurred, the flow length decreased and the sinuosity and curvature will decrease as a consequences (Frascati and Lanzoni, 2010; Hooke, 2004; Rhoads et al., 2016; Yousefi et al., 2016). The channel migration was highest in the second study period (1989–1995), which

is likely to reflect channel response to disturbance by a large flood in 1986 and another in 1995. The number of cutoffs and new meanders for this period are 4 and 9, respectively, and the movement of channel is extremely high. Fig. 11 shows the morphological evolution in some meander loops during the study period.

4.2. Hydrology and geomorphology

One of the problems in the present study is the uncertainty between the study reach and hydrological station (about 10 km). However, we assumed that the hydrological regimes along the study reach have the
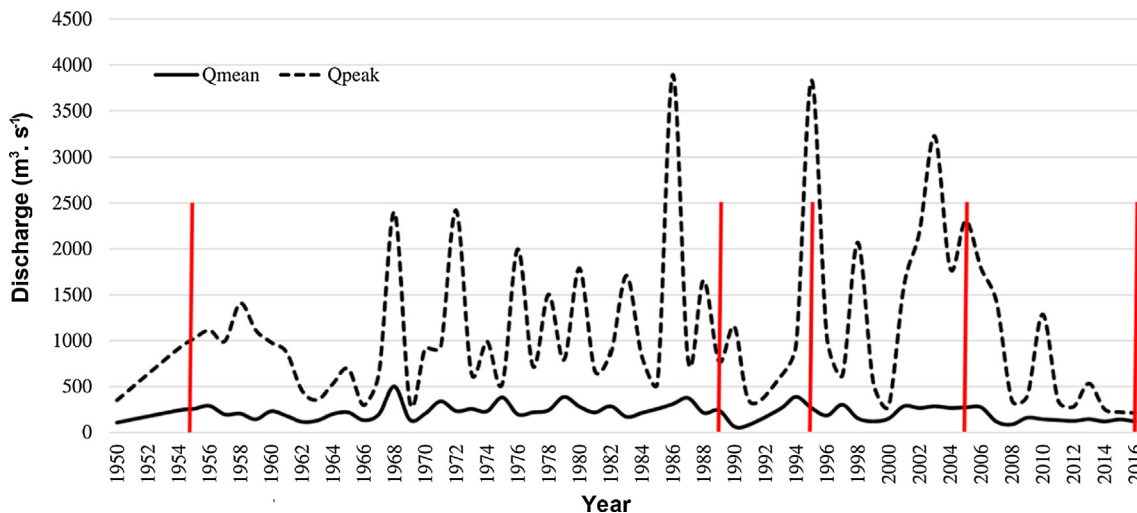

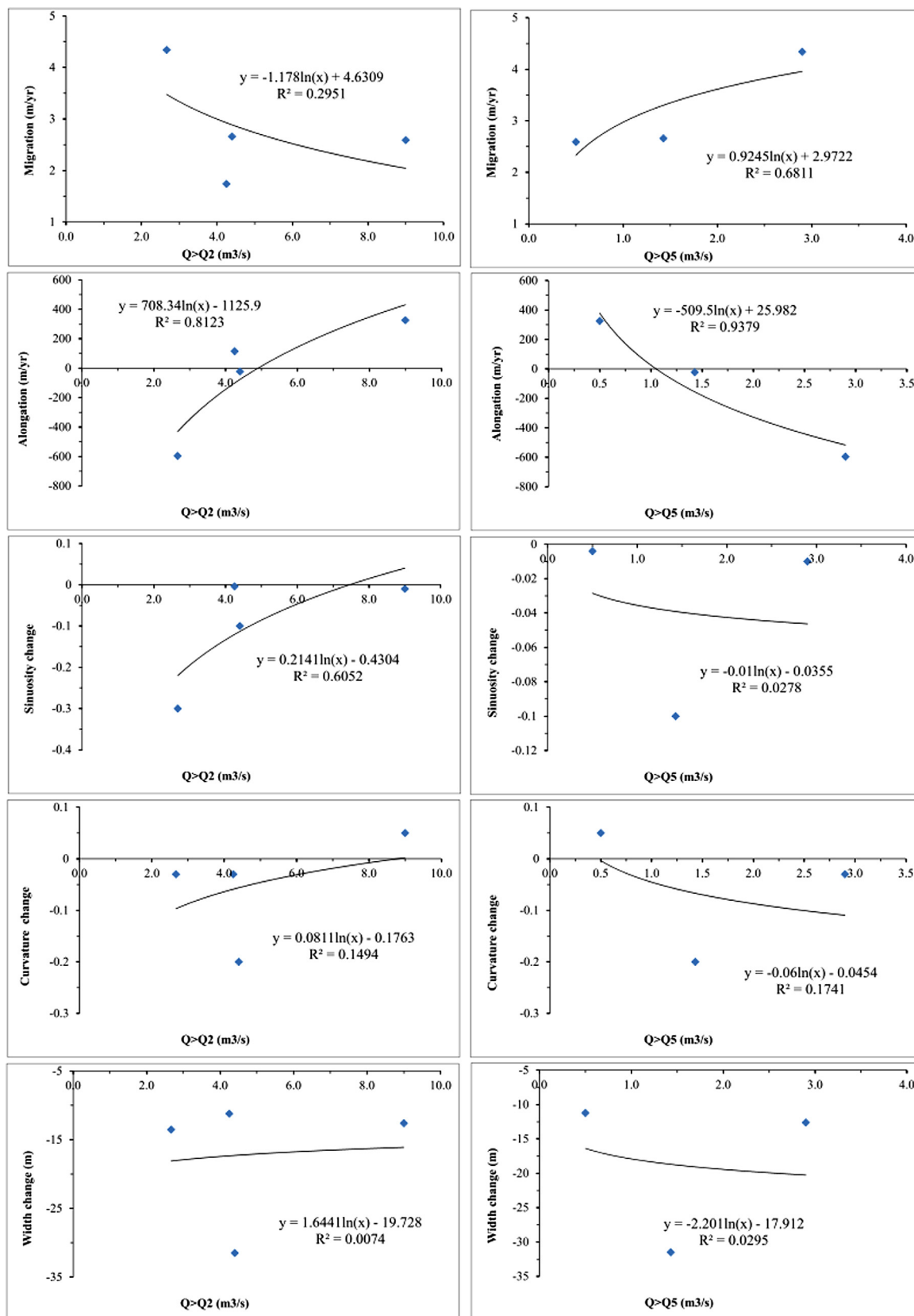**Fig. 9.** Annual average and peak discharge during study period.

Fig. 10. Correlation between frequency of hydrological events and geomorphological evolution in the study reach.

same behavior, in the absence of significant tributaries. The Dezful gauging station provides the best option for hydrological analysis in this study. The results of Pearson correlation showed that the type of

correlation between the frequency of hydrological events (flood days) are bigger than Q2 and the elongation of channel is directly correlated. This suggests that the greater the number of flood days bigger than Q2,
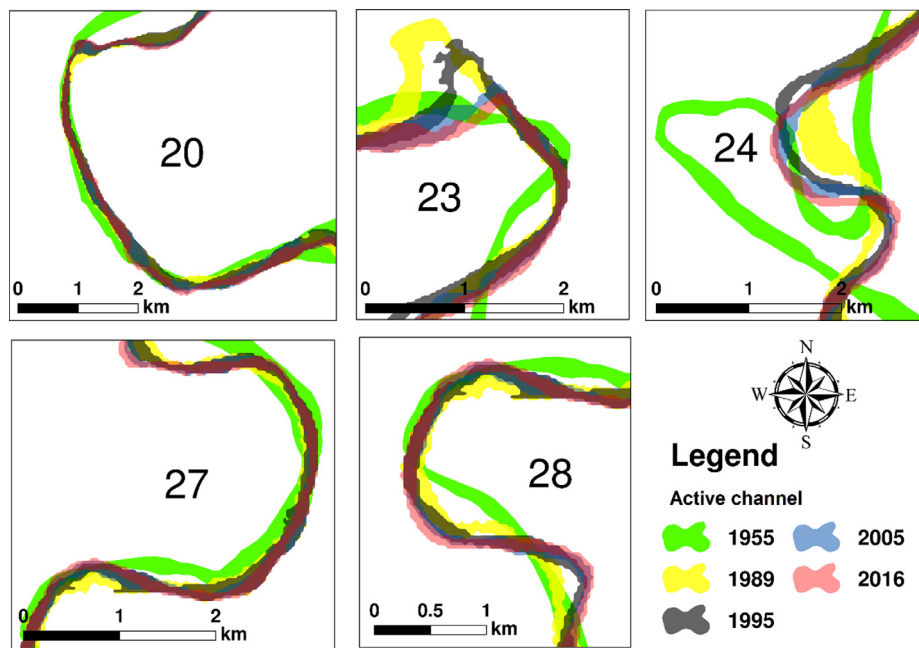
Fig. 11. Morphological evolutions in some meander loops in the Dez River.

the length of the river is expected to increase. However, this relationship for events bigger than Q5 is inverse. Hydrological events less than Q5 play an important role to form the meander loops and the length of the flow will be longer (Camporeale and Ridolfi, 2010; Dépret et al., 2015). By increasing the frequency of floods bigger than Q5, increasing the power of discharge, the bank retreat and the probability of cutoffs occurring in channels will be greater. Channel migration and bank retreat in the study reach have a direct, significant correlation with the frequency of floods greater than Q5. It is generally accepted that bank retreat occurs during hydrological events larger than average (Das et al., 2014; De Rose and Basher, 2011; Posner and Duan, 2012). Dépret et al. (2015) stated that increasing the number of flood days directly increased bank retreat and channel migration. The sinuosity index change and frequency of hydrological events bigger than Q2 have a significant direct correlation, but for frequency of events bigger than Q5 there is no significant correlation with sinuosity change. This can be explained with changes in the flow rate of the river. During periods of higher discharge, bank retreat and channel movement will straighten the course via cutoffs (Hooke, 2004; Rhoads et al., 2016; Toone et al., 2014).

The active channel width of large rivers is mostly controlled by human management actions and very large hydrological events such as flash floods and extreme floods (Alexandrov et al., 2007; Borga et al., 2007; Hooke, 2016). The results here show that the width of the Dez River in the study reach is not significantly correlated with flood frequency (Table 4). Therefore, it is likely that channel reinforcement by river managers plays a definitive role in keeping the width of the river stable during larger floods, and resulting in an overall narrowing.

The lack of data available on water management (including irrigation) in the study reach precludes discussion of the effects of water use in agriculture along the Dez River. Almost all irrigation in the study area uses traditional systems and there is no available data to inform the process of irrigation and water management systems. Further studies should investigate the effects of irrigation and water management on the fluvial evolution of study reach. In this study all the data were generated following the Dez dam construction. The effects of this dam on the Dez River fluvial geomorphology during the study period have not been assessed as a result.

5. Conclusion

The evolution of the Dez River in a 153 km reach during 61 years (1955–2016) was investigated and assessed alongside the hydrological record for the period. The relationship between the frequency of $Q > Q2$ and $Q > Q5$ and morphological changes in the study reach were considered in particular. Our findings indicate that the study reach of the Dez River underwent a significant channel narrowing in response to human intervention, rather than any changes in flow magnitude or frequency. The reduction in sinuosity of the study reach was associated with larger floods causing cutoffs, demonstrated by channel elongation. During the study period, 17 new meanders and 9 cutoffs were created along the study reach. Channel migration was maximized during a large-flood dominated period in the late 1980 s and early 1990 s.

Hydrological events with different return periods play different roles in the morphological evolution in the study reach of the Dez River. Cutoffs and higher migration rates are dependent on extreme and larger discharge events, while progressive bend development takes place during periods dominated by smaller flood events. The findings of this study could help understand the evolution of fluvial systems, particularly where flooding regimes are predicted to change in response to warming climate.

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Further Reading

Beechie et al. (2006) investigated the channel pattern and river-floodplain dynamics in a forested watershed, finding that spatial mobility of straight channels is lower than meandering channels.